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SECRETARY



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PREFACE.

THE present volume of the *Journal of the Iron and Steel Institute* contains twenty-two papers presented at the Annual Meeting, held in London in May 1923, with the discussion and correspondence thereon. In addition to these twenty-two papers a report by F. C. Langenberg (Watertown, Mass.) on the "Results of an Investigation of the Behaviour of Certain Steels under Impact at different Temperatures," and a paper by T. Matsushita (Sendai, Japan) on "Investigations on the Quenching of Carbon Steels," were submitted at that Meeting. Mr. Langenberg's work, being a report on research work carried out with the aid of a grant from the Carnegie Scholarship Fund, has been transferred to Volume XII. of the *Carnegie Scholarship Memoirs*, published this year, while the paper by Mr. Matsushita has been printed in abstract in its appropriate place in Section II. of this volume of the Journal.

At the end of the volume is inserted a list of the British Standardised Steel Samples issued jointly by the Iron and Steel Institute and the National Physical Laboratory, showing the terms on which they are obtainable.

For lack of space it has been found necessary to postpone the publication of the usual Obituary. The list of names of those Members who died during the year will be found recorded in the Report of Council.

Section II. contains, as usual, notes on the progress of the home and foreign iron and steel industries, as reported in the

proceedings of scientific and technical societies and in the technical press, together with a bibliography of the principal works dealing with the metallurgy of iron and steel, mining, and allied subjects, which have appeared during the past six months.

Attention is also drawn to an alteration in the method of indexing. Certain signs have been used in the Index to denote in the case of any entry whether such entry refers to a complete paper, to a subject incidental to the general subject of the paper, to a contribution to the discussion of a paper, or finally to an abstract.

28 VICTORIA STREET LONDON, S.W. 1.
August, 1923.

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THE
IRON AND STEEL INSTITUTE.

SECTION I.
MINUTES OF PROCEEDINGS.

ANNUAL MEETING, 1923.

THE ANNUAL MEETING of the IRON AND STEEL INSTITUTE was held at the Institution of Civil Engineers, Great George Street, Westminster, on Thursday and Friday, May 10 and 11, 1923, Mr. FRANCIS SAMUELSON, President, occupying the Chair.

FIRST DAY, THURSDAY, MAY 10, 1923.

The Minutes of the last General Meeting were taken as read and confirmed.

SCRUTINEERS.

Mr. W. CROSS (London) and Mr. NOEL RIDSDALE (Middlesbrough), who had been elected scrutineers of the ballot for the election of new members, announced that the following seventy-two candidates for membership and sixteen candidates for associateship had been duly elected :

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Goodrich, William Edward	155 Hunter House Road, Sheffield	C. H. Desch, T. Swinden, P. B. Henshaw.
Gospel, Walter	65 Seventh Avenue, Heaton, Newcastle-on-Tyne	H. J. Young, C. Gresty, G. W. Hewson.
Hill, Francis William	Apedale Hall, Newcastle, Staffs.	F. W. Harbord, C.B.E., D. E. Roberts, W. Simons.
Hlott, Edward James	128 Lower Road, Belvedere, Kent	A. E. Pratt, R. Whitfield, G. Melland.
Jay, Henry Cecil	97 Cardigan Terrace, Heaton, Newcastle-on-Tyne	C. Gresty, G. W. Hewson, H. J. Young.
Keay, George Albert	31 Melville Street, Pollokshields, Glasgow	J. H. Andrew, W. Regan, Jr., J. Lennox.
Lester, Alan Edgar	27 Augustus Road, Edgbaston, Birmingham	G. Hatton, H. C. H. Carpenter, I. E. Lester.
McWilliam, John Abram, B.A. (Cantab.)	1 Den Bank Avenue, Sandygate, Sheffield	C. H. Desch, W. H. Hatfield, G. R. Bolsover.
Pearson, Claude Edmund	2 Pearl Street, Saltburn-by-the-Sea	C. H. Desch, W. H. Hatfield, E. W. Jackson.

NAME.	ADDRESS.	PROPOSERS.
Rayner, Philip John, B.Met.	1 Baker Street, Sheffield	C. H. Desch, E. Gregory, Cosmo Johns.
Thomas, James Malcolm	15 Greenfield Villas, Llanelly	A. Job, D. G. Evans, J. C. Godsell.
Walters, John Price, B.Sc.	Brecon House, Queens- ferry, Chester	F. C. Thompson, H. P. Smith, C. Bottomley.
White, Harold John	9 Grange Crescent Road, Sharrow, Sheffield	C. H. Desch, E. Gregory, C. Handford.

The following four Associates have been transferred to full membership :

Berry, Walter Richard.
Cawley, Frank Bennett.

Rogerson, Robert Bond.
Wakley, Henry Weston.

REPORT OF THE COUNCIL FOR THE YEAR 1922.

The SECRETARY read a *résumé* of the Report of the Council for 1922, the text of which will be found on p. 12.

STATEMENT OF ACCOUNTS FOR 1922.

Mr. ILLTYD WILLIAMS, Hon. Treasurer, in presenting the accounts for 1922, said that some satisfaction might be derived from the fact that even so small an amount as £24 19s. 8d. appeared as surplus of income over expenditure, as it had been feared that the balance for the year would be on the wrong side. The very anxious period through which the industry had passed in 1921 and 1922 affected them in two ways—by decreasing the number of new members, and by causing many resignations. There was also a decrease in receipts from Journal sales. On the expenditure side salaries had risen by about £295, and in office rent and cleaning there was an increase of nearly £254. Practically the whole of that was due to the fact that they had had to renew their lease on higher terms. The cost of the “Autumn Meeting” had been £187. That meeting was rather suddenly decided upon, and more than the usual expenditure had consequently been entailed. Journal publishing expenses had increased by £303. Whether the cost of printing the Journal would ever come down to a moderate figure again it would be unwise to prophesy. In

1922 the two vols., containing some 1200 pages between them, cost £1952 17s. 10d. for printing, binding, and paper. In 1913 the two vols., containing 1557 pages, cost only £1265 9s. 1d. He trusted that better times would ensue, that the membership would increase, and that the larger income so secured would enable the surplus of future years to be more considerable.

On the motion of the PRESIDENT the Report of Council and the Statement of Accounts were unanimously adopted.

PRESENTATION OF THE BESSEMER MEDAL.

The PRESIDENT said he had great pleasure in presenting the Bessemer Gold Medal for the year to Dr. Maw. Dr. Maw was born at Scarborough in 1838, and was educated privately. In 1855 he became a pupil in the Eastern Counties Railway Works, now the Great Eastern Works, at Stratford, under the late Mr. John Gooch, and in 1859 he became head draughtsman in the locomotive and engineering department, in which capacity he designed locomotives for the Great Luxemburg Railway and for the East Indian Railway, those for the latter being the first outside cylinder engines used on Indian railways. In 1865 Dr. Maw joined the late Mr. Zerah Colburn in founding the well-known technical journal *Engineering*, and in 1870 Dr. Maw became joint editor with the late Mr. James Dredge. Dr. Maw had done a great deal for the advancement of engineering practice. From 1870 until within a few years ago, Dr. Maw carried on an independent practice as a consulting engineer, his chief work being in connection with engine and boiler construction, and the design and arrangement of workshops and similar buildings. In addition to many addresses and papers read before various engineering institutions, Dr. Maw was joint author of "The Waterworks of London" and of "Road and River Bridges," while "Recent Practice in Marine Engineering" long remained a standard record of developments in that department of science. He was one of the founders and Presidents of the Civil and Mechanical Engineers' Society, and was President of the Institution of Mechanical Engineers in 1901 and 1902, and of the Institution of Civil Engineers in 1922. Dr. Maw was a Member of the General

Committee of the National Physical Laboratory, and during the war served on the Advisory Panel of the Munitions Inventions Department. Dr. Maw was almost as well known for his work in astronomy as well as for that in engineering, and was President of the Royal Astronomical Society in 1905. In 1909 the University of Glasgow conferred on him the degree of LL.D.

Dr. W. H. MAW thanked the President, and through him the Council and the members, for the honour conferred upon him. The award had an additional value to him in that it was associated with the name of Sir Henry Bessemer. He was first introduced to Sir Henry Bessemer at the London Exhibition of 1862. At that time they were experimenting with, and using to a certain limited extent, steel for locomotive axles and tires on the Great Eastern Railway. Sir Henry Bessemer had a most interesting exhibit at the Exhibition, and he (Dr. Maw) spent a good deal of time with him in going through it and learned much by what he was told. Sir Henry Bessemer and he became intimate friends, a friendship which lasted up to the time of Sir Henry's death.

ALTERATION OF BYE-LAW 10.

The PRESIDENT said that at the Autumn Meeting at York in September 1922 notice had been given that a resolution would be submitted at the Annual Meeting in May 1923, proposing an alteration of Bye-Law 10 specifying the period during which the President should hold office. The terms of the resolution were that the first two lines of the present Bye-Law 10, which read :

“The President shall be elected for two years and shall not be eligible for re-election until after an interval,”

should be altered to read as follows :

“The President shall be elected for one year,”

and that the words, “and shall not be eligible for re-election until after an interval,” be omitted. No notice of any amendment to that resolution having been given at the last meeting, he would now put it to the meeting for acceptance or rejection.

The resolution was then put and declared by the President to have been carried unanimously.

The following papers were then read and discussed :

- E. R. SUTCLIFFE and E. C. EVANS, "The Reactivity of Coke as a Factor in the Fuel Economy of the Blast-Furnace."
 F. CLEMENTS, "British Steel Works Gas-Producer Practice."
 J. E. FLETCHER, "Some Characteristics of Moulding Sands and their Graphical Representation."

The meeting was adjourned at 1 P.M. to 2.30 P.M., when the following papers were read and discussed :

- J. H. WHITELEY and A. BRAITHWAITE, "Some Observations on the Effect of Small Quantities of Tin in Steel."
 H. C. H. CARPENTER, "The Production of Single Metallic Crystals and some of their Properties."
 J. O. ARNOLD, "On the Correlation of the Chemical Constitutions of 'True Steels' to their Micrographic Structures."

CARNEGIE SCHOLARSHIP AWARDS.

On the resumption of the meeting on Friday, May 11, the SECRETARY announced that the following grants of Carnegie Scholarships had been made :

- CECIL HANDFORD, B.Met. (University College, Cardiff), £100 to carry out research work on the behaviour of metals within and at the limits of the elastic range.
 C. W. H. HOLMES, B.Met. (Birtley, Durham), £100 to conduct investigations on the macrostructure of cast iron.
 W. R. D. JONES (University College, Cardiff), £100 to continue his work on the silica materials of South Wales, with special reference to the influence of texture.
 F. S. MERRILLS (Musselburgh), £100 to study the fatigue of metals.
 E. L. REED (Harvard University, U.S.A.), £100 for investigation on the structure and physical properties of iron-carbon alloys melted and heat-treated *in vacuo*.
 J. G. R. WOODVINE (Shrewsbury), £100 to carry out a research on the effect of carburising and complete case-hardening upon the fatigue properties of typical commercial case-hardening steels.

The following had received further grants of £50 :

- A. L. CURTIS (Chatteris, near Cambridge) to continue research on steel moulding sands and their behaviour under high temperatures.

- A. M. PARKIN (The University, Sheffield), to continue research on the influence of heat treatment and of variable carbon content upon a magnet steel with a constant tungsten composition.
- J. H. WHITELEY (Stockton-on-Tees) and A. F. HALLIMOND (Geological Survey, London), a joint grant to enable them to continue their researches on the nature of pearlite.

The following papers were then read and discussed :

MORNING SESSION.

- C. A. ABLETT, "Economic Principles governing the Use of Electrical Power in Iron and Steel Works."
- C. H. DESCH and A. T. ROBERTS, "Some Properties of Steels containing Globular Cementite."
- T. P. COLCLOUGH, "The Constitution of Basic Slags—Its Relation to Furnace Reactions."
- D. HANSON and J. R. FREEMAN, "The Constitution of the Alloys of Iron and Nickel."

AFTERNOON SESSION.

- C. A. EDWARDS and C. R. AUSTIN, "A Contribution to the Study of Hardness."
- H. O'NEILL, "The Variation of Brinell Hardness Number with Testing Load."
- J. STEAD, "The Cold-Working of Steel with Reference to the Tensile Test."
- C. R. AUSTIN, "Some Mechanical Properties of a Series of Chromium Steels."
- J. J. A. JONES, "The Acl Range in Alloy Steels."
- F. C. LANGENBERG, "An Investigation of the Behaviour of Certain Steels under Impact at Different Temperatures."¹

VOTES OF THANKS.

On the motion of the PRESIDENT, a hearty vote of thanks was accorded to the Institution of Civil Engineers for the accommodation granted the Institute for the meeting.

¹ This paper, which embodied the results of a Carnegie Scholarship Research award, together with the correspondence thereon, will be published in the forthcoming volume of Carnegie Scholarship Memoirs (Vol. XII.).

On the motion of Mr. A. HUTCHINSON, Member of Council, a hearty vote of thanks was accorded the President for presiding.

The PRESIDENT, in reply, said it was, in one way, a difficult task to preside at the Institute's meetings, because of the necessity of constantly hurrying through the sessions, due to the fact that the Institute really tried to get through a great deal too much in the time at its disposal. Possibly if fewer papers were presented more time could be given to their reading and discussion, and the meetings would gain both in value and in comfort. He thanked those present for the support they had afforded him in the chair, and for the vote they had passed.

The proceedings then terminated.

The following papers, which had been submitted for reading, were taken as read, and are printed for record in the present volume :

- J. W. LANDON, "Change of Density of Iron due to Overstrain."
- A. GOFFEY and F. C. THOMPSON, "The Changes in Iron and Steel below 400° C."
- L. NORTHCOTT, "A Note on Temper Carbon."
- T. F. RUSSELL, "The Potential Energy of Cold-worked Steel."
- E. J. L. HOLMAN, "Note on a Value for the Surface-tension of Iron Sulphide."
- L. E. BENSON and F. C. THOMPSON, "Some Experiments on Grain Growth in Iron and Steel." (Part I.)
- K. HONDA and T. MURAKAMI, "On the Structural Constitution of Iron-Carbon-Silicon Alloys."
- T. MATSUSHITA, "Some Investigations on the Quenching of Carbon Steels." (Printed in abstract only, in Section II.)

REPORT OF COUNCIL.

THE Council of the Iron and Steel Institute have much pleasure in submitting at this, the Fifty-fourth Annual General Meeting, their Report on the proceedings and work of the Institute during the year 1922.

ROLL OF THE INSTITUTE.

During the year under review eighty-four new members and nine associates were elected, and nine associates were transferred to membership, the total membership on the register of the Institute on December 31, 1922, being made up as follows :

Patron	1
Honorary Members	6
Life Members	80
Ordinary Members	2023
Associates	37
<hr/>	
Total	2147

Sixty-seven members and two associates resigned their membership, and the names of fifty-three members and three associates were removed from the register owing to the non-payment of their subscriptions.

The deaths of the following twenty-four members were reported to the Council during the year :

Akerman, General Direktor R., Hon. Member (Stockholm)	February 23.
Bostwick, W. A. (New York)	February 4.
French, E. L. (Syracuse, U.S.A.)	August 31.
Harris, G. (Ebbw Vale)	May 25.
Hill, J. A. (Sheffield).	December 13.
Holliday, H. (Harrow)	May 4.
Howe, Professor H. M., Hon. Vice-President (New York)	May 14.
Hubert, Professor H. (Liège)	September 30.
Jackson, J. (Newport, Mon)	January.
Jones, T. W. (Swansea)	January 28.
Lees, J. B. (Manchester)	March.
Lobley, H. D. (Sutton)	October 14.

Maclay, D. M. (St. Andrews)	April 30.
McWilliam, A., C.B.E. (Sheffield)	April 5.
Middleton, J. T. (London)	June 22.
Morton, B. K. (Wimbledon)	February 6.
Noyes, H. (Melbourne)	April.
Shaw, F. T. (Middlesbrough)	February 6.
Simpson, A. (Edinburgh)	March 26.
Stevens, S. E. (Doncaster)	November 10.
Taylor, K. (New Jersey)	April 4.
Vassar-Smith, Sir R. V. (London)	August 2.
Walker, W. E. (Whitehaven)	November 9.
Wardlow, M. (Sheffield)	October 5.

The deaths of the following six members occurred prior to 1922, but were not reported to the Council until that year :

Allison, J. A. (Bilbao)	December 9, 1921.
Ashforth, W. D. S. (Mossend)	October 2, 1921.
Bramall, C. (Sheffield)	November, 1921.
Harrison, J. W. (Wakefield)	September 24, 1921.
Hollis, H. E. (Glasgow)	December 15, 1921.
Wood, E. F. (New York)	January 5, 1920.

The Council desire sincerely to express their sense of the loss of their esteemed Honorary Member, Dr. Richard Akerman, Bessemer Medallist, and a member of the Institute for over forty-seven years, and of their distinguished Honorary Vice-President, Dr. Henry Marion Howe, to whom the Bessemer Medal had similarly been awarded in 1895. By the deaths of Professor McWilliam, Mr. J. T. Middleton, and Professor Hubert the Institute has likewise been deprived of the loyal support those members had for many years afforded it.

HONOURS CONFERRED ON MEMBERS OF THE INSTITUTE.

The Council have much pleasure in offering congratulations to those members of the Institute upon whom honours have been conferred during the year. Mr. J. C. Davies has had the honour of a knighthood conferred upon him, and Mr. H. E. Oving has been made a Knight-Officer of the Order of Oranje Nassau by H.M. the Queen of the Netherlands. Mr. Carlo Vanzetti has been made a Commander of the Order of the British Empire, and Mr. C. F. Rand (Honorary Member) has had conferred upon him the Cross of a Chevalier of the Legion of Honour. The President, Mr. Francis Samuelson, was, on the occasion of the Scientific Congress at Liège, elected President of Honour. Mr. George Hatton, C.B.E., was made High Sheriff of the County of Worcester, while amongst the important technical appointments

made during the year the Council have pleasure in noting that Professor G. B. Waterhouse has been made head of the Department of Metallurgy at the Massachusetts Institute of Technology, while Dr. Percy Longmuir has been appointed Director of Research to the British Cast Iron Research Association. The Watt gold medal of the Institution of Civil Engineers has been awarded to Mr. S. A. Main. Sir William Larke, K.B.E., has been appointed director of the National Federation of Iron and Steel Manufacturers.

FINANCE.

The Statement of Accounts for the year 1922 is presented by the Honorary Treasurer, Mr. Iltyd Williams, for approval, having been duly audited and vouched for by Messrs. W. B. Keen & Co., the Institute auditors. The income for the year under review was £7964, exclusive of the Carnegie Scholarship Fund. The expenditure was £7939. The comparative figures of income and expenditure for the last five years are shown below :

	Income.	Expenditure.
	£	£
1917	5427	5202
1918	5792	6128
1919	5979	7088
1920	8419	7622
1921	8349	6866

The principal item in the expenditure, apart from salaries, is on account of the printing of the Journal. The charges maintained by the printing trades are still exceedingly high, and the expenses involved in the preparation of illustrations are likewise considerably above pre-war rates. It will be noted, too, that the rent for the Institute offices has also been increased. Nevertheless, it is satisfactory to note that, notwithstanding these heavy expenses, the accounts this year still show a small balance on the right side.

MEETINGS.

By kind permission of the Council of the Institution of Civil Engineers the Annual Meeting was held, on Thursday and Friday, May 4 and 5, at the hall of that Institution, the chair being taken by Mr. Francis Samuelson, who was inducted as President by Dr. Arthur Cooper, Past-President, in the unavoidable absence of the retiring President, Dr. J. E. Stead, F.R.S. The Council wish to avail themselves of the present occasion to express their deep regret at the illness which prevented Dr. Stead from attending, and to convey to

him their sincere desire for the complete recovery of his health, and their earnest hope that he may again be able to attend the meetings of the Institute, whose prosperity he has always had so greatly at heart.

The Annual Dinner was held at the Connaught Rooms on the evening of Thursday, May 4, and was attended by some 300 members and guests. Speeches were delivered by Sir William Ellis, G.B.E., Vice-President, by the Right Hon. Edward Shortt, K.C., M.P., at that time Home Secretary, by the Right Hon. Sir Eric Geddes, G.C.B., G.B.E., LL.D., by the Right Hon. the Lord Inchcape, and by the President.

The Autumn Meeting was held in York, which was selected as a convenient centre from which members could avail themselves of the kind invitation given by Mr. Charles Markham and his co-directors to visit the works of the Staveley Coal and Iron Company, and those of the Park Gate Iron and Steel Company, at Chesterfield and Rotherham respectively. The business sessions of the Institute were held, by kind permission of the Council of the Yorkshire Philosophical Society, at the Museum, York, on Tuesday and Wednesday, September 5 and 6, under the chairmanship of the President, the opening session being attended by the Deputy Lord Mayor of York (Mr. Alderman E. Walker), and by the General Manager of the North-Eastern Railway Company (Mr. R. C. Wedgwood, C.B., C.M.G.), who welcomed the visitors to York. On the afternoon of Tuesday, September 5, a film demonstration was given by Mr. W. McConway in the Festival Rooms, illustrative of his new process for the centrifugal casting of steel discs; while in the afternoon of Wednesday, September 6, a garden-party was held in the grounds of the Philosophical Society adjoining the Museum. The evening was devoted to a *conversazione* and dance in the Corporation Art Gallery, while the two following days were taken up by excursions to Chesterfield and Staveley, when the members visited the works of the companies to whom reference has been made, and were entertained on both days at luncheon by Mr. Markham and the Directors with cordial and generous hospitality. On the afternoon of Thursday, September 7, a party of members and ladies visited Rievaulx Abbey, and a dinner was held on the evening of that day at the Assembly Rooms, York. Members were also invited during the Meeting to visit the works of Messrs. T. Cooke & Sons in York. The thanks of the Council are gratefully tendered to all those who so cordially helped to render the York Meeting the success which, by the unanimous verdict of the members attending, it was conceded to have been.

Twenty-two papers were contributed to the proceedings of the Institute during the year, and have been reprinted, together with the discussions and correspondence thereon, in the Journal. The complete list is as follows :

- AITCHISON, L., and G. R. WOODVINE—"The Changes of Volume of Steels during Heat Treatment. I. Air-Hardening Nickel-Chromium Steels."
 AUSTIN, C. R.—"Hydrogen Decarburisation of Carbon Steels, with Notes on Related Phenomena."
 BELAEW, N. T.—"The Inner Structure of the Pearlite Grain."
 BENSON, L. E.—"Nitrogenisation of Iron and Steel by Sodium Nitrate."
 CAMPBELL, E. D.—"A Brinell Machine Attachment for Use with Small Specimens."
 CAMPBELL, E. D., and E. R. JOHNSON—"A Preliminary Magnetic Study of some Heat-treated Carbon Steels."
 CARPENTER, H. C. H., and Miss C. F. ELAM—"Effect of Oxidising Gases at Low Pressures on Heated Iron."
 CLEMENTS, F.—"British Siemens Furnace Practice."
 DICKENSON, J. H. S.—"Some Experiments on the Flow of Steels at a Low Red Heat, with a Note on the Scaling of Heated Steels."
 EHN, E. W.—"Influence of Dissolved Oxides on Carburising and Hardening Qualities of Steel."
 HALLMOND, A. F.—"On Delayed Crystallisation in the Carbon Steels: the Formation of Pearlite, Troostite, and Martensite."
 HOLMES, C. W. H.—"An Investigation on the Factors Influencing the Grain and Bond in Moulding Sands."
 HONDA, K.—"On the Constitutional Diagram of the Iron-Carbon System, based on Recent Investigations."
 HONDA, K., and T. KIKUTA—"On the Stepped A1 Transformation in Carbon Steel during Rapid Cooling."
 OGILVIE, H. K.—"Practical Notes on the Manufacture and Treatment of High-Speed Steel."
 REESE, A. K.—"The Bases of Modern Blast-Furnace Practice."
 ROBERTS, D. E.—"Notes on Blast-Furnace Filling."
 SELBY-BIGGE, D.—"Recent Developments in Power Production."
 WESTGREN, A., and G. PHRAGMÉN—"X-Ray Studies on the Crystal Structure of Steel."
 WHITELEY, J. H.—"The Diminution of Lag at Ar1 through Deformation."
 WHITELEY, J. H.—"Formation of Globular Pearlite."
 YAMADA, N.—"On the Heat of Transformation of Austenite to Martensite, and of Martensite to Pearlite."

BESSEMER MEDAL.

The Bessemer Gold Medal for the year 1922 was awarded by the Council to Professor Kotaro Honda (Sendai, Japan) for his distinguished services to the advancement of the metallurgy of iron and steel.

ANDREW CARNEGIE RESEARCH SCHOLARSHIPS.

Grants were made by the Council, on the recommendation of the Carnegie Scholarship Committee, to the following candidates :

- A. BRAMLEY (£100) for investigations on the carburising and decarburising effects of different gases on iron and steel.

- A. L. CURTIS (£100) for investigations on steel moulding sands and their behaviour under high temperatures.
- O. W. ELLIS (£100) for investigations on the effect of constitution on malleability at high temperatures.
- J. N. FRIEND (£100) for researches on corrosion.
- E. M. PARKIN (£100) for investigations on the influence of heat treatment and variable carbon content upon magnet steel of constant tungsten composition.
- G. V. PHRAGMÉN (£100) for investigations on the specific weight of molten metals.
- W. E. WILLIAMS (£100) for investigations on X-ray spectrography as applied to examining the structure of steel.

PUBLICATIONS.

The publications of the Institute during 1922 comprised two volumes of the Journal, aggregating nearly 1200 pages; a volume of Carnegie Scholarship Memoirs, containing 168 pages; and the usual list of members (174 pages). An index to the *Proceedings* and *Journals* comprising the period 1911-1921 (eleven years) is in course of being printed, and will be issued to the members during the early part of this year.

ADDITIONS TO THE LIBRARY.

The additions made to the collection of books include the following donations from authors, publishers, and others, to whom the Council take this opportunity of extending their thanks: "L'Étude de la Structure des Métaux et Alliages et ses Conséquences," by A. M. Portevin; "Causes d'Usure Premature des Rails," by C. Fremont; "The Manufacture of Iron and Steel," 2nd edition, by H. R. Hearson; "The Homogeneous Electrothermic Effect," by C. Benedicks; "Mechanical Testing," Vol. I., "Testing of Materials of Construction," by R. G. Batson and J. H. Hyde; "The Work and Position of the Metallurgical Chemist," by Sir R. Hadfield; "Fifty Years of Iron and Steel," by J. G. Butler, jun.; "Electro-Deposition of Iron," by W. E. Hughes; "Two Centuries of Iron Smelting in Pennsylvania," by R. Peters, jun.; "Metallurgy of Iron and Steel," by Sir R. Hadfield; "The Rocks and Contact Minerals of the Mansjö Mountains," by H. von Eckermann; "Biographies of John Fritz Medallists," compiled by the John Fritz Medal Board of Award; "Geology of the An-Shan Iron Mine District, South Manchuria," by H. Murakami; "Coal in International Trade," by A. J. Sargent; "Steel Thermal Treatment," by J. W. Urquhart; "Hütte: 1923—i.

Taschenbuch für Eisenhüttenleute," 2nd edition; "Metallographie," Vol. I. Part II. No. 2, Vol. II. Part I. No. 3, by W. Guertler; "The Development of Stainless Steel," by Thomas Firth & Sons, Ltd.; National Physical Laboratory—"Collected Researches"; "The Determination of the Thermal Conductivity, Specific Heat, Density, and Thermal Expansion of Different Rocks and Refractory Materials," by Y. Tadokoro; Imperial Mineral Resources Bureau—"Iron Ore: Summary of Information as to the Present and Prospective Iron Ore Supplies of the World," Parts I. to VIII.; "Theory of Wave Transmission," 2nd edition, by G. Constantinesco; "Report on the Railway Systems of Kenya, Uganda, and Tanganyika," Parts I. to III., by F. D. Hammond; Alfred Herbert, Ltd.—"The Industrial Application of the Ball Hardness Test, with Brinell Number Tables"; and "Trade and Industry of Finland."

Among the books that have been purchased are: "Aluminium and its Alloys," by C. Grard; "Case-hardening of Steel," 2nd edition, by H. Brearley; "The Electric Furnace," by J. N. Pring; "The Electro-Metallurgy of Steel," by C. C. Gow; "The Geology of the British Empire," by F. R. C. Reed; "General Foundry Practice," 3rd edition, by A. McWilliam and P. Longmuir; "The Precious Metals," by Sir T. K. Rose; "Electric Welding," by E. Viall; "Failure of Metals under Internal and Prolonged Stress"; "Metallographie," 2nd edition, by G. Tammann; "The Coal Resources of the World," Vols. I. to III.; "Iron Foundry Practice," by G. J. Pitt; "Scientific Papers of B. Hopkinson"; "Report on Materials of Construction used in Aircraft," by C. F. Jenkin; "A Dictionary of Applied Chemistry," Vols. III. and IV., revised edition, by Sir Edward Thorpe; "An Introduction to the Study of Metallography and Macrography," by L. Guillet and A. M. Portevin; "Einführung in die Metallographie," 3rd and 4th editions, by P. Goerens; "Practical Alloying," 2nd edition, by J. F. Buchanan; "Conditions et Essais de Réception des Métaux," 2nd edition, by G. Charpy; "Deterioration of Structures of Timber, Metal, and Concrete exposed to the Action of Sea Water," Second (Interim) Report of the Committee of the Institution of Civil Engineers; "Metallography," 3rd edition, by C. H. Desch; "Foundrymen's Handbook"; "Handbook on the Winning and Utilisation of Peat," by A. Hausding; "The Geology and Mineral Resources of the Serb-Croat-Slovene State," by D. A. Wray; "Annual Tables of Constants and Numerical Data," Vol. IV. Part II.; "The Determination of Sulphur in Iron and Steel," by H. B. Pulsifer; and "American Malleable Cast Iron," by H. A. Schwartz.

APPOINTMENT OF REPRESENTATIVES.

The President continues to represent the Institute on the General Committee of the Royal Society for administering Government Grants for Scientific Investigations. Sir Robert Hadfield, Bart., F.R.S., and Professor Henry Louis represent the Institute on the Board of the National Physical Laboratory, and Sir Hugh Bell, Bart., represents the Institute on the Board of Governors of the Imperial College of Science and Technology. The Institute representatives on the British Engineering Standards Association are Dr. A. Cooper, Mr. M. Mannaberg, and Mr. B. Talbot. On the Sub-Committee of that Association, for the Standardisation of Galvanised Sheets, Mr. C. Dorman continues to serve; while Mr. H. J. Yates and Dr. W. H. Hatfield are the Institute representatives on the Sub-Committee for Cast Iron, working under the direction of the Sectional Aircraft Committee; Mr. J. H. S. Dickenson represents the Institute on the Technical Committee of Motor Industries; and Mr. F. W. Harbord on the Sectional Committee for Chemical Engineering. On the newly formed Sub-Committee for the purpose of preparing standard specifications for cement from blast-furnace slag, the Institute is likewise represented by Mr. Harbord. Lord Invernairn of Strathnairn, Mr. H. Brearley, Mr. J. H. S. Dickenson, Mr. D. Flather, and Dr. W. H. Hatfield represent the Institute on the Committee on Special Steels for Automobile and Aircraft Construction of the Institution of Automobile Engineers. Mr. Harbord is the representative on the British Refractories Research Association, and Dr. Cooper, Mr. Mannaberg, Mr. G. Hatton, C.B.E., and Mr. Talbot represent the Institute on the Committee on the Improvement and Development of Basic Slag, formed by the Ministry of Agriculture and Fisheries. Professor T. Turner represents the Institute on the Grey and Malleable Iron Research Committee of the Department of Scientific and Industrial Research. On the Technical Committee of Lloyd's Register of British and Foreign Shipping the Institute is represented by Lord Invernairn and Mr. L. Ennis. Sir Robert Hadfield, Bart., F.R.S., and Professor Louis represent the Institute on the Conjoint Board of Scientific Societies, and Sir Robert Hadfield also represents the Institute on the British Association Fuel Economy Committee, on the Court of Sheffield University, and on the Home Committee for the University of Hong Kong; while on the Courts of Liverpool University and of Bristol University the Institute is represented by Sir W. Peter Rylands and Mr. W. R. Lysaght, C.B.E., respectively. Mr. Harbord is the

representative on the Advisory Board of the Royal School of Mines, and, with Sir Robert Hadfield, represents the Institute on the Federal Council for Pure and Applied Chemistry.

CHANGES ON THE COUNCIL.

Mr. Francis Samuelson has been elected to the Presidency of the Institute, and Sir Frederick Mills, Bart., has been elected a Vice-President to fill the vacancy thus created, Mr. John Craig, C.B.E., having been elected a Member of Council in his place. His Honour Judge Elbert H. Gary has been made an Honorary Vice-President to fill the vacancy occasioned by the death of Professor Howe, and Dr. Carl Benedicks has been added to the list of Honorary Vice-Presidents.

The names of the following Vice-Presidents and Members of Council were announced at the Autumn Meeting as being due to retire (in accordance with Byelaw 10) at the Annual Meeting in 1923, but as being eligible for re-election. No fresh nominations having been received, the retiring members are presented for re-election.

Vice-Presidents—Mr. C. J. Bagley ; Sir William H. Ellis, G.B.E. ; Mr. M. Mannaberg.

Members of Council—Mr. F. W. Gilbertson ; Mr. E. H. Saniter ; Mr. John Craig, C.B.E. ; Professor H. Le Chatelier ; and Sir John S. Randles.

STATEMENT OF ACCOUNTS.

ACCOUNT OF INCOME AND EXPENDITURE FOR THE YEAR ENDED DECEMBER 31, 1922.

INCOME.			EXPENDITURE.		
To Entrance Fees	...	£189 0 0	By Salaries (including Overtime)	...	£3176 9 6
" Annual Subscriptions (Members)	...	£6030 13 2	" Office Rent, Cleaning, &c...	...	982 19 2
" Do. (Associates)	...	47 5 0	" Library Books and Binding	...	202 18 0
" Life Compositions	...	...	" Office Furniture	...	53 6 11
" Journal Sales	...	...	" Autumn Meeting	...	237 2 2
" Interest on Investments, <i>Less</i> Tax	...	£533 19 7	" Annual Meeting	...	106 11 1
" Income Tax recovered to March 31, 1922	...	162 7 0	" Journal Publishing Expenses:—	...	...
" Bessemer Medal Fund:—	...	...	Printing, &c.	...	£1952 17 10
Interest on Investments, <i>Less</i> Tax	...	£11 8 3	Abstracts	...	109 12 4
Income Tax recovered to March 31, 1922	...	4 16 2	Translations	...	3 1 10
" Interest on Deposit	...	...	Postage	...	150 8 2
" Surplus on change of Investment Securities	...	...	Stationery and Printing (including copies of Papers)...	...	2216 0 2
" Sundry Receipts	...	...	" Postage and Receipt Stamps	...	478 8 0
			" Travelling Expenses	...	159 10 1
			" Insurance	...	49 17 8
			" Telephone	...	25 17 11
			" Auditor's Fee	...	24 10 5
			" Bessemer Medals	...	31 10 0
			" Compassionate Allowance	...	44 5 0
			" Sundry Payments	...	60 0 0
				...	92 1 7
				...	7939 8 8
			Excess of Income over Expenditure carried to Balance Sheet		24 19 8
					£7964 8 4

THE IRON AND STEEL INSTITUTE.

SPECIAL PURPOSES FUND—BALANCE SHEET, DECEMBER 31, 1922.

LIABILITIES.		ASSETS.	
Capital Account, representing subscriptions received 1919-20	£9451 0 0	£12,242 19s. 3d. 4 per cent. Funding Stock, 1960-90	... £9,512 7 5
Invested <i>per contra</i> ...	... £9451 0 0	Cash at Bank:	...
Amount due to Iron and Steel Institute ...	... 19 4 6	Current Account ...	... £ 70 3 1
Income and Expenditure Account:	...	Deposit Account ...	... 541 0 6
Balance at 1st January 1922 ...	£551 5 10		611 3 7
Add Excess of Income over Expenditure for	102 0 8		
the year ended 31st December 1922 ...	653 6 6		
	<u>£10,123 11 0</u>		<u>£10,123 11 0</u>

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED DECEMBER 31, 1922.

INCOME.		EXPENDITURE.	
To Interest on Funding Stock	£355 1 0	By Grants:	£250 0 0
" Interest on Deposit	9 0 0	Alloys Research Committee	...
" Income Tax recovered	146 18 1	British Refractories Research Association	... 25 0 0
		Board of Conjoint Societies	... 10 0 0
		" Advertisement of British Steel Standards	...
		" Copies of Technical Papers for a Technical Committee	... 9 0 0
		" Excess of Income over Expenditure	... 408 18 5
	<u>£510 19 1</u>		102 0 8
			<u>£510 19 1</u>

INVESTED FUNDS OF THE INSTITUTE.

£1000 War Loan 5 per cent. 1923-47, cost...	...	...	...	...	...	£945 16 4
£543 19s. 2d. 3½ per cent. Conversion Loan, cost...	...	...	...	...	...	409 11 0
£1000 Commissioners for the Port of Calcutta 4 per cent. Bonds 1939, cost	...	...	...	...	...	982 10 0
£800 Trustees of the Port of Bombay 4 per cent. Bonds 1939, cost	...	...	...	...	...	809 0 0
£374 14 North-Eastern Railway 4 per cent. Preference Stock, cost	...	...	...	...	...	4,297 6 7
£788 North-Eastern Railway 4 per cent. Guaranteed Stock, cost	...	...	...	...	...	1,008 14 0
£750 Great Central Railway 3½ per cent. Second Debenture Stock, cost	...	...	...	...	...	659 12 6
£750 Great Central Railway (Leeds, Bradford, and Halifax) 6 per cent. Guaranteed Stock, cost...	...	...	...	...	...	1,140 8 6
£511 South-Eastern Railway 3½ per cent. Perpetual Debenture Stock, cost	...	...	...	...	...	449 4 5
£1500 Buenos Ayres Great Southern Railway 4 per cent. Debenture Stock, cost	...	...	...	...	...	1,594 12 9
£79 4s. 5d. "B" Annuity Scinde, Punjab, and Delhi Railway, expiring 1958, with a Sinking Fund to replace the amount of Stock, cost	...	...	...	...	...	1,999 0 7
£50 1s. 8d. "B" Annuity, Great Indian Peninsular Railway, expiring 1948, with a Sinking Fund to replace the amount of Stock, cost	...	...	...	...	...	1,267 6 0

INVESTMENTS ON ACCOUNT OF LIFE COMPOSITIONS.

£1330 North-Eastern Railway 3 per cent. Irredeemable Debenture Stock, cost	...	...	...	...	...	£15,563 2 8
£335 North British Railway 4½ per cent. Irredeemable Preference Stock, cost	...	...	...	...	...	£1,254 17 6
£335 London Electric Railway 4 per cent. Perpetual Debenture Stock, cost	...	...	...	...	...	371 13 9
£335 Metropolitan District Railway 4 per cent. Prior Lien Debenture Stock, cost	...	...	...	...	...	304 14 11
£681 13s. Funding Loan 4 per cent. 1960-1990, cost	...	...	...	...	...	333 11 2
	...	...	...	...	...	600 0 0
	...	...	...	...	...	£2,864 17 4
	...	...	...	...	...	£9,512 7 5

INVESTMENT ON ACCOUNT OF SPECIAL FUND.

£12,242 19s. 8d. 4 per cent. Funding Stock, 1960-1990, cost	£9,512 7 5
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ANDREW CARNEGIE RESEARCH SCHOLARSHIP FUND.

£2250 Newcastle-upon-Tyne Electric Supply 4½ per cent. Consolidated First Mortgage Debenture Stock, cost	£2,261 10 0
£2000 Great Central Railway 3½ per cent. Second Debenture Stock, cost	...	...	...	...	...	2,055 13 6
£2600 Great Central Railway 4½ per cent. Debenture Stock, cost	...	...	...	...	...	2,384 6 0
£5000 Great Northern Railway 3 per cent. Debenture Stock, cost	...	...	...	...	...	3,186 16 9
£5000 Great Eastern Railway 4 per cent. Debenture Stock, cost	...	...	...	...	...	4,080 16 0
£2000 North British Railway 3 per cent. Debenture Stock, cost...	...	...	...	...	...	1,249 12 6
£2000 Caledonian Railway 4 per cent. Debenture Stock, cost	...	...	...	...	...	1,693 0 6
£1500 Great Western Railway 4 per cent. Debenture Stock, cost	...	...	...	...	...	1,204 5 3
£2560 4s. India 3 per cent. Stock, cost	...	...	...	...	...	1,525 3 3
£2300 India 3½ per cent. Stock, cost...	...	...	...	...	...	1,600 2 9
£1000 War Loan 5 per cent. 1923-47 (Surplus Income), cost	...	...	...	...	...	£21,241 5 6
	...	...	...	...	...	906 10 6
	...	...	...	...	...	£22,146 16 0

(Signed) ILLFYT WILLIAMS, Hon. Treasurer. G. O. LLOYD, Secretary.

I have examined the foregoing Balance Sheets and Income and Expenditure Accounts with the Books and Vouchers of the Institute, and certify them to be correct. I have also verified the Balances and the Securities for the Invested Funds shown above.

23 QUEEN VICTORIA STREET, E.C. 4 : 5th April 1923. (Signed) W. B. KEEN, Chartered Accountant.

BESSEMER MEDAL FUND (Trustees: Sir HUGH BELL, Bart., Lord AIREDALE, and FRANCIS SAMUELSON, Esq.).
 £534 London and North-Western Railway 3 per cent. Debenture Stock.

Iron and Steel Institute.

THE REACTIVITY OF COKE AS A FACTOR IN THE FUEL ECONOMY OF THE BLAST- FURNACE.

BY E. R. SUTCLIFFE AND EDGAR C. EVANS.

WITH A NOTE BY R. V. WHEELER.

THE most authoritative recent British contribution to the study of fuel economy in the iron and steel industry was the report of the British Association Committee presented to the Institute in 1919 by Professor Bone, Sir Robert Hadfield, and Mr. Hutchinson.¹ The section dealing with blast-furnace practice was based to a great extent upon the work of Sir Lowthian Bell and his famous dictum, that "it was useless to hope to smelt a ton of grey iron from the Cleveland stone yielding 41 per cent. of pig metal with anything notably under 20½ cwt. of coke," was quoted as apparently still representing the practicable minimum of fuel economy. The final conclusion arrived at in connection with blast-furnace economy is summarised as follows: "It would hardly be economical . . . to reduce the coke consumption on the blast-furnace below the proportion necessary to provide the minimum number of heat units in the outgoing gases necessary to carry out, in combination with the surplus coke-oven gas, the operations of the plant as a whole without further expenditure of coal either in gas-producers or under boilers."

It is not proposed to deal in this present paper with the last contention, which can only be decided by individual ironworks "after a very careful review of the requirements of the plant as a whole." The following notes deal with the blast-furnace, not as a glorified gas-producer, but in its primary function as an apparatus for the reduction of iron ore.

Apparently the general tendency in modern plants is to secure the highest possible economy in the blast-furnace operations, and to instal supplementary plant for additional heat requirements. In the case of new plant this seems the logical method

¹ *Journal of the Iron and Steel Institute*, 1919, No. II. p. 11.

of procedure, if only for the reason that the blast-furnace is such an expensive gas-producer that the cost of production per B.Th.U. of gaseous fuel produced would probably be considerably higher than that produced in plant specially designed for the purpose. This question, too, is however outside the scope of this paper. The main question to be dealt with is the limit to which the fuel consumption can be reduced in the actual smelting operation itself.

The eminence of the authorities presenting the above report, and the evident importance attached by them to the work of Bell on the subject, makes it necessary at the outset to review that work in the light of modern knowledge, and to raise the question whether his views regarding fuel economy still represent the last word on the subject.

BELL'S THEORIES ON FUEL CONSUMPTION.

The opinion quoted above was based on the facts proved experimentally in exhaustive researches, that the indirect reduction of ore ceased at temperatures below 480°C. , when the proportion of $\text{CO} : \text{CO}_2$ in the reducing gases was less than 2 : 1. From this result Bell assumed that once this ratio had been reached in the furnace gases, "the action would be delayed until the mineral reached a level in the furnace, when the heat would resolve any carbon dioxide into carbon monoxide."¹ If this view be correct, the limiting reaction could be represented by the equation :



which requires, for its solution, a carbon consumption equivalent to 19.35 cwts. per ton of iron produced. After allowing for the carbon required by the iron, the impurities in the coke, &c., this would account for a coke consumption of some $20\frac{1}{2}$ to 21 cwts.

Whilst Bell tried to extend this hypothesis as widely as possible, he cautiously limited its precise application to the production of No. 3 iron from Cleveland ore (Fe, 41 per cent.) with the use of Durham coke.² It is well known that many furnaces are working with a far lower consumption of fuel and

¹ *Journal of the Society of Chemical Industry*, 1890, p. 709.

² "Chemical Phenomena of Iron Smelting," p. 238.

a considerably lower $\text{CO}:\text{CO}_2$ ratio than is required by the above equation, and it is necessary at the outset to determine the effect of those limitations on the fuel consumption.

The additional carbon required for the manufacture of No. 3 iron can be readily ascertained, as also the fuel required for fluxing the additional slag on Cleveland ore as compared with that of rich ores. These two points are dealt with later, together with the influence of the character of the coke. The immediate point is—Does Cleveland ore possess some characteristic which makes it more difficult to reduce than other ores, and which in itself necessitates a higher fuel consumption?

It is well known that some ores are more irreducible than others, and the effect of the physical characteristics of an ore on its ease of reducibility is also well known. Does Cleveland ore possess any special characteristics which make it difficult to reduce? In replying to a contribution by Bell on a paper by Gayley¹ on American blast-furnace practice, the latter referred to some results he had obtained from American ores in comparison with Cleveland and Lancashire ores, showing that Cleveland ore was more easily reducible than high-class American ore, while Wright² gives the results of experiments on different ores, which indicate that Cleveland ore has, under certain conditions, the highest degree of reducibility.

Apparently then, apart from its low iron content, Cleveland ore does not possess any special characteristics which would *per se* necessitate a higher fuel consumption.

The next question that arises is whether it is possible, under blast-furnace conditions, for a condition of equilibrium to be reached between the ore and the reducing gases which would allow of a definite fixed ratio between the CO and CO_2 being attained. Those gases pass through the furnace with an enormous velocity. Johnson³ has calculated that the time between the entry of the blast at the bottom of the furnace and its escape from the top in the form of gas may, in modern furnaces, be as short as two seconds. Generally speaking, in laboratory experiments, involving reactions between solids and gases, a very

¹ *Transactions of the American Institute of Mining Engineers*, 1890, vol. xix. p. 932.

² *Journal of the Iron and Steel Institute*, 1920, No. I. p. 183.

³ "Principles, Operations and Products of the Blast-Furnace," p. 117.

considerable time is taken before equilibrium conditions are reached, and it does not seem reasonable to suppose that, in the exceedingly short space of time during which the reducing gases are in the furnace, equilibrium could be attained.

Lastly, if Cleveland ore does not possess any physical characteristics which make it difficult to reduce, how can the low fuel consumptions recorded by Bell himself, and by other observers in the case of charcoal and other furnaces, be accounted for? These low consumptions are accompanied invariably by a low $\text{CO} : \text{CO}_2$ ratio; and in this connection the extraordinary results obtained by Gayley with dry-blast can be cited where the $\text{CO} : \text{CO}_2$ ratio fell from 1.7 to 1.25, with a corresponding reduction in fuel consumption of 2260 lbs. to 1815 lbs. These results cannot be accounted for by any theory of equilibrium ratio. It is as well to face the position at the outset, and after allowing to the full for the value of Bell's wonderful pioneer work, there seems to be no valid reason for believing that the fuel economy of a blast-furnace is entirely dependent upon reactions taking place in the upper 20 feet or so. If this be so, Bell's theory falls to the ground; and under suitable conditions the $\text{CO} : \text{CO}_2$ ratio, even with Cleveland ore, could be considerably reduced below the "minimum" assigned by Bell, thus allowing of a reduction in fuel consumption.

Interest in this question has been quickened by the remarkable results obtained in modern furnaces within recent years. Howland,¹ for example, gives detailed particulars of a series of American furnaces all working Mesaba ores, in twenty of which the $\text{CO} : \text{CO}_2$ ratio fell below 2.1, and in sixteen of which the ratio fell below 1.7. At the same time a revolutionary development has taken place in blast-furnace theory which, if correct, is so radical as to necessitate a complete recasting of the views advanced by Bell.

JOHNSON'S THEORIES OF BLAST-FURNACE PRACTICE.

In 1905 Johnson² advanced his hypothesis of the "critical temperature" as a controlling factor in blast-furnace operations.

¹ *Transactions of the American Institute of Mining Engineers*, 1917, vol. lvi. p. 339.

² *Ibid.*, 1905, vol. xxxvi. p. 454.

This theory is presented very fully in Johnson's book on blast-furnace practice and need not be restated here. How far this theory has been accepted by British experts is doubtful. Johnson states that it has been rejected in Germany, whilst Potter¹ has shown that it does not hold good for cupola practice. It appears, therefore, to have definite limitations; but, on the other hand, the conception accounts for blast-furnace phenomena in a manner which necessitates its being taken into serious account in any review of blast-furnace theory.

Johnson states that there are two zones of heat generation in a blast-furnace: (1) The combustion zone at the hearth, where the carbon is oxidised by the oxygen in the blast to carbon monoxide, and (2) the shaft, where the carbon monoxide thus produced is further oxidised by the oxygen in the ore to carbon dioxide. In so far as the hearth is concerned, it is necessary to attain a certain critical temperature—which Johnson assumes to be the free running temperature of the slag—and certain operations can only be carried out above this temperature, these probably comprising the removal of the last portions of oxygen, the formation and superheating of the cinder, and the melting, carburisation, and superheating (above fusion point) of the iron. The difference between the critical temperature and the temperature of combustion determines the "available heat" for these operations. This "available heat" has a pronounced effect upon the fuel economy of the blast-furnace. It accounts, for example, according to Johnson, in a *quantitative* manner for the fuel economies effected by hot-blast, and even for the remarkable results obtained by dry-blast. Richards,² in discussing the saving effected by Gayley with dry-blast, pointed out that the whole of the saving in fuel, which could have been predicted from theory, was only about 3·5 per cent. of the heat value of the coke used, whilst the actual saving was over 19·6 per cent.

Assuming a figure of 2750° F. for the critical temperature in Gayley's furnace, Johnson calculates that the available heat on the data supplied was 1090 and 1420 B.Th.U.'s per lb. of fuel with moist and dry blast respectively. The coke consumption

¹ *Transactions of the Eighth International Congress of Applied Chemistry*, 1912, sec. 111A, p. 135.

² *Transactions of the American Institute of Mining Engineers*, 1905, vol. xxxvi. p. 745.

before the change was 2140 lbs., afterwards it was 1700 lbs.; whilst if it were in inverse proportion to the available heats it would be 1640 lbs. The difference between the practical result and the theoretical calculation is so small that the conception of "available heat," or rather of "hearth heat," as it is now called, is one that merits detailed attention.¹

The $\text{CO} : \text{CO}_2$ ratio, according to Johnson's conception, becomes a matter not of definite established chemical equilibrium, but of simple arithmetic. Each unit of iron requires for its final reduction and melting in the hearth a definite quantity of hearth heat. To produce this, a definite quantity of fuel must be burnt to carbon monoxide. A proportion is oxidised by the oxygen in the ore to produce carbon dioxide, resulting in a final mixture of these gases in a proportion depending entirely upon chemical arithmetic.²

It is evident that this theory differs radically from Bell's. Bell's "cause" of fuel consumption—the chemical equilibrium between carbon monoxide, carbon dioxide, and ore in the upper region of the furnace, depending on the $\text{CO} : \text{CO}_2$ ratio—becomes with Johnson an "effect," governed entirely by the carbon consumption required to produce the necessary hearth heat. Whether the theory be one which will stand the test of time in every detail or not, it is one which lends valuable help in attacking some of the more obscure problems in blast-furnace technology and opens up very interesting possibilities of reducing fuel consumption, particularly in the direction of increasing the hearth heat. Before proceeding, however, it might be advisable to touch very briefly on the present general aspects of blast-furnace practice in England.

THE BRITISH BLAST-FURNACE.

A most valuable analysis of British blast-furnace practice was given by Clements in 1920.³ The accurate and detailed chemical and thermal balance-sheets give at first sight very little hope of improvement being effected. Every unit of heat supplied to the furnace seems to be satisfactorily accounted for, and it is

¹ Cf. J. E. Johnson, "Principles, &c.," p. 33 *et seq.*

² Johnson, *op. cit.*, p. 151.

³ *Journal of the Iron and Steel Institute*, 1920, No. I. p. 125.

extremely difficult—even presumptuous—to point to this or that item on the balance-sheet and to state definitely that this or that saving could be effected. Yet, from a purely general standpoint, there must surely be room for improvement. Taking the three groups of furnaces detailed in Table I. by Clements, the position can be summarised thus :

	Pig Iron Yield. Per Cent.	Coke per Ton of Iron. Per Cent.	Carbon per Ton of Iron. Per Cent.
Midland section .	30	29·0	23·4
Cleveland section .	35	22·36	18·77
S. Wales section .	48	20·26	16·19

Even after allowing for the additional heat requirements necessitated by the low iron content of the ores used by the Midland section, there would seem to be considerable scope for reduction in fuel consumption.

Theoretically, if pure iron ore could be reduced in accordance with the equation—



the total carbon requirements would only amount to $6\frac{1}{2}$ cwts. per ton of pig iron, whilst, as will be shown later, the chemical and thermal requirements can be satisfied—for pure ore—with an expenditure of only 8·6 cwts. of carbon per ton of pig iron. Mr. Clements, as the result of his analysis, came to the conclusion that :

- “ 1. For a furnace built on good lines there is little hope of economies being effected on the “ Heat Absorbed ” side of the Balance Sheet.
- “ 2. Given a certain set of conditions as far as blast temperature is concerned, the economy in carbon consumption depends entirely upon the proportion burnt to carbon dioxide.”

In other words, we are back again at the $\text{CO} : \text{CO}_2$ ratio !

In this connection, however, it must be pointed out that the production of a higher proportion of carbon dioxide will not only involve a lower carbon consumption on the “ Heat Produced ” side of the Balance Sheet, but will also effect economies on the “ Heat Absorbed ” side, chiefly in the following directions :

- A. The item “ Sensible heat in exit gases ” would be reduced, owing to the smaller quantity of blast that would be required to burn the smaller quantity of carbon.

- B. The reduced carbon consumption would require less coke, and less slag (from this coke) would be produced. The "Heat in Molten Slag" would therefore be reduced.
- C. Arguing from results obtained in cases where fuel economies have been effected by the introduction of hot-blast, dry-blast, &c., radiation and other losses per unit of iron would be reduced.

In other words, fuel economy is cumulative in character and affects both sides of the "Thermal Balance Sheet," with practical results that are generally considerably greater than those which would be deduced simply from a consideration of the "Heat Produced" side. Any method, therefore, which can result in an increase in the proportion of carbon dioxide is one which is worthy of very serious attention on the part of the blast-furnace manager.

When it comes to specific suggestions as to how this can be effected, so many factors are involved that it is extremely difficult to cover them even in a general way. This is especially true where the question is dealt with by investigators who are not engaged in the industry itself.

The influences which determine an increase in the carbon dioxide percentage in blast-furnace gas can perhaps be summarised as follows :

1. *Blast-Furnace Design.*

This question in its general aspects is outside the province of this paper. There is, however, one point of a theoretical character which can be mentioned, as it raises in the mind of an outsider to the industry the question whether the blast-furnace in its present general form is an ideal instrument for the smelting of iron.

The influence of furnace design on fuel economy was recently treated by Reese¹ in another paper. Whiting² quoted the case of two furnaces using the same ores, fuels, and fluxes, but varying in shape, size, and rate of driving. In one case the fuel consumption was 12.8 cwts. of carbon per ton of iron with a $\text{CO} : \text{CO}_2$

¹ *Journal of the Iron and Steel Institute*, 1922, No. II. p. 9.

² *Transactions of the American Institute of Mining Engineers*, 1891, vol. xx. p. 281.

ratio of 1·5; in the other it was 14·9 cwts. of carbon per ton of iron with a ratio of 2·38. At the close of his paper a very interesting statement is made to which it is worth drawing attention. In the operation of the more efficient furnace a change was made from a burden containing all ore to one containing a large proportion of scrap. In the latter case it was found necessary to have an excess of coke (after satisfying the requirements of the ore), so that 1 lb. of coke dealt with 3·2 lbs. of scrap.

In the ordinary cupola 1 lb. of coke will melt 10 lbs. of scrap—why, therefore, was this great excess required in the blast-furnace? Whiting considered that the reason was that reoxidisation of the iron took place by carbon dioxide in its passage down the furnace. Figures on this point from British furnaces would be of considerable interest, but if this result be representative of ordinary practice, it raises a very important question as to the means that could be adopted in minimising or reducing such secondary reactions.

Bell's earlier view was that the bulk of the oxygen in the ore was removed in the first 20 feet of its descent in the furnace. By 1890, however, he had come to the conclusion that about 25 per cent. of the oxygen remained in the ore in the form of a suboxide and was not removed until it reached the vicinity of the tuyeres.¹ More recently, Johnson assumed that 10 per cent. of the oxygen in the ore had to be removed by solid carbon in the hearth.² Is this oxygen the result of imperfect reduction at the top of the furnace, or is it due to secondary oxidation in the shaft?

If the latter, it results in a thermal loss which may be important, and if it can be reduced either by slight modifications in furnace design, or alternatively, as is suggested later, by modifying the character of the fuel, the result should be an appreciable saving in fuel consumption.

2. *Character of the Materials used.*

The materials entering the blast-furnace consist of: (1) Ore; (2) limestone; (3) blast; (4) coke.

¹ *Journal of the Iron and Steel Institute*, 1891.

² J. E. Johnson, *op. cit.*, p. 79.

Ore and Limestone.—The influence of the physical characteristics of these materials—apart entirely from the chemical characteristics—has recently been emphasised by Mr. Reese,¹ and there is no need in this paper to do more than once again point out the effect of structure, particularly of the ore, in increasing its “reactivity to the action of the reducing gases.”

Blast.—It is a remarkable fact that the most notable results in the direction of fuel economy have been effected by treating the blast, especially by increasing its temperature and by its dehydration. There is a further possibility now opening out in the increase of its oxygen content. The results obtained by dry-blast were so important as to lead the authors to believe that an increase of but 5 per cent. in the oxygen content of the blast would be attended by marked results. The cost of each such enrichment, even under present conditions of oxygen production, should not be too high to make the matter one worthy of being tried, while new developments are taking place which should result in the production of oxygenated air in the near future at a cost low enough to bring it within reach of practically every furnace. If Johnson's theory be sound, the theoretical possibilities of an increase of 5 per cent. of oxygen in the blast are sufficiently attractive to make the matter one worthy of trial.

Fuel.—Modern theory places the critical zone of the blast-furnace, in so far as fuel economy is concerned, at the hearth, where the principal reactions take place between the oxygen and the fuel. Blast-furnace men rightly attach considerable importance to the character of the fuel used, and as the result of generations of experience have been led to demand special qualities in the coke supplied to them. Before proceeding to discuss these, it might be advisable to mention the twofold functions of a blast-furnace fuel. It has to supply (1) the heat necessary to satisfy the thermal requirements of the furnace, and it has (2) to supply the carbon necessary for the reduction of the ore. Both combustion and reduction are chemical processes, and it might have been anticipated that in the length of time during which the blast-furnace has been in use that a tendency would have evinced itself in the direction of securing in the fuel a property which is now being recognised as one of the

¹ *Journal of the Iron and Steel Institute*, 1922, No. II. p. 9.

most important in chemical operations where solids are used—the property of “reactivity.” There does not, however, appear to be any pronounced demand in this direction, and the principal qualities asked for to-day by British workers appear to be those sought forty years ago.

The most recent statement of the essentials of a good blast-furnace coke is that of Mr. Reese,¹ and the following summary of his requirements can probably be taken as representing modern British views on the subject.

Essentials of a Blast-Furnace Coke.

1. Freedom from ash and sulphur.
2. High carbon content.
3. Resistance to the action of CO_2 in the upper region of the furnace.
4. Rapidity of combustion. To secure this, the size of the coke lumps must not be too great.
5. Uniformity of size. A maximum size of 4 to 6 inches, and, on the other hand, freedom from smalls.
6. Strength without “density,” as “density” is inimical to rapid combustion and fast driving.
7. Porosity—or highly developed cellular structure—which, however, must not be so open as to reduce strength, with the subsequent production of smalls.
8. Hardness—to resist abrasion in the furnace.

The above summary introduces some requirements which were not generally recognised in Bell’s time, when the principal requisites of a fuel were: (1) Low sulphur; (2) resistance to CO_2 ; (3) strength; and (4) hardness. A coke was preferred which was silvery grey in colour and “rang” when struck with a hammer. The demand for a pronounced cellular structure and for rapidity of combustion is a more or less modern development, and in this portion of the specification there is a tentative move in the direction of a “reactive” fuel.

Taking the above requirements in detail, some of the qualities asked for are of a character which are above criticism. The

¹ *Op. cit.*

necessity, for example, of a low sulphur and ash content is admitted by all, and recent innovations in cleaning coal offer possibilities of supplying a coke of a degree of purity that, except in special cases, has not hitherto been obtainable. In so far as the third requirement is concerned, resistance of the coke to solubility in carbon dioxide, the authors venture to propound the heresy that this quality, far from being detrimental, is actually one of the most valuable that a coke can possess. The question, however, is dealt with in detail later on.

PHYSICAL PROPERTIES OF COKE.

Apart from the porosity, cellular structure, and size of the coke charged, qualities closely related to its combustibility and therefore dealt with later, the principal qualities required in a blast-furnace coke are strength, to withstand the weight of the burden, and hardness, so that the coke may suffer as little abrasion as possible during its passage through the furnace. The authors do not wish to minimise the importance of a sufficient degree of strength and hardness in a coke to prevent its being ground up in a furnace. A careful analysis of the position raises, however, the question whether these qualities are so desirable as have hitherto been supposed. A remarkable paper on this subject was read as far back as 1879 by Professor Church,¹ dealing chiefly with the relative qualities of coke, anthracite, and charcoal as blast-furnace fuels. Some of the points raised in that paper are touched upon later, but in referring to the qualities of strength, &c., required, the author remarks: "Blast-furnace managers require a coke, hard, strong and ringing—in fact, they want every quality that charcoal does not possess; perhaps by making a lighter article, avoiding high heats in coking, and aiming to produce a porous delicate coke, it might be possible for a coke furnace to draw nearer her charcoal sister in economy of fuel."

As the result of his studies, Church ventured at the close of his paper to raise the question whether the objection to a "weak" fuel on the part of the blast-furnace manager was not a chimera, and whether it would not be better to sacrifice

¹ *Transactions of the American Institute of Mining Engineers*, 1878, vol. vii. p. 33.

some proportion at any rate of the "strength" of coke with a view to securing a higher degree of combustibility.

The objections to a weak coke are well known, but if a coke is strong enough to withstand the burden and to resist excessive abrasion, that is all that is required, and if by the sacrifice of a proportion of these qualities a higher degree of combustibility can be gained, it will be to the advantage in securing a greater fuel economy in the furnace.

SOLUBILITY OF COKE IN CARBON DIOXIDE.

There is hardly any quality in coke which has been more strongly condemned than that of its solubility in carbon dioxide. Every writer on the blast-furnace from Bell to Johnson, every fuel technologist, and every coke-maker, has almost unanimously recorded his opinion that this action is one of the most deleterious to fuel economy that can be experienced. This conclusion has been arrived at on practical as well as theoretical grounds, and has been supported on the laboratory side. Bell made a number of experiments. He showed that soft coke was affected at 427°C ., whilst good hard coke was not acted on until a temperature of 815°C . was attained. Further, the relative solubilities of hard and soft coke in carbon dioxide at 800°C . were in the ratio of 1 : 2.

On the practical side Bell quotes a test¹ in which soft coke was tried in a blast-furnace, with the result that the carbon dioxide in the furnace gases showed a considerable diminution for some time. This test, however, does not appear to be a very conclusive one. A much more exhaustive test² was made at the Clarence Works with a large batch of soft coke made after lighting up some new ovens. "The quantity of carbon dioxide found in the gases, per ton of iron made, fell considerably, and the consumption of coke rose in proportion." Bell extended the view relating to solution of carbon by carbon dioxide to the direct action of carbon upon the ore. The action results in a loss of heat, owing to the endothermic character of the reaction. Bell showed that the power of carbon to act on oxide of iron

¹ "Principles of the Manufacture of Iron and Steel," p. 102.

² *Ibid.*, p. 196.

was modified by its physical condition—charcoal, for example, being much more active than coke. His views as to loss of heat by solution were afterwards confirmed by Fulton.¹ Investigating the reasons for the marked inferiority of Johnstown coke as compared with Connesville coke in the blast-furnace, Fulton came to the opinion that the results obtained were due to “softness of body” in the Johnstown coke, causing it to be ignited in the upper regions of the furnace, not only wasting its heat there, but disarranging the operations of the furnace. Fulton’s conclusions were based upon laboratory experiments only.

The laboratory and practical experiments made by the above authorities are supported to some extent by the inferior results obtained by blast-furnace managers when soft coke is used, and, generally speaking, the high fuel consumptions recorded in such cases are attributed to high solution losses. On the theoretical side likewise there is a very considerable weight of expert opinion in favour of the view that solution loss is a very serious factor in high fuel consumption. Gruner, for example, in 1879 propounded his well-known theory that the condition of ideal working required the fuel burnt by the blast at the tuyeres to be a maximum and that dissolved by the oxygen of the charge a minimum; in other words, solution loss in the upper region of the furnace, whether occasioned by carbon dioxide or by the oxygen in the ore, is a cause of increased consumption of fuel.

That view is emphasised by Johnson,² both on theoretical and practical grounds. Johnson found in working a charcoal furnace on rich ores that when the departure from Gruner’s ideal working is considerable, as shown by the small quantity of blast required to burn a pound of fuel, the fuel economy is poor, and when the quantity of blast to burn a pound of fuel goes up, the fuel economy increases in the same proportion, in exact accordance with Gruner’s theorem. On the theoretical side Johnson devotes the whole of Chapter V. of his work to a consideration of the thermal effects of loss of fuel by solution. In a series of detailed and careful calculations he demonstrates the effect of solution losses under varying conditions in the blast-furnace, his work thus lending

¹ *Transactions of the American Institute of Mining Engineers*, 1883, vol. xii. p. 212.

² J. E. Johnson, *op. cit.*, p. 75.

powerful support to the popular view that a coke of high solubility is an inferior one for blast-furnace purposes.

Taking a general view of the question, it seems at first sight a thankless task to challenge the formidable body of expert opinion outlined in the above summary, and to venture to propound the theory that a high solubility factor is an advantage in a coke. Yet, if a careful analysis be made of the evidence on which this opinion is based, it does not seem so overwhelming as it appears at first sight; whilst, on the other hand, arguments can be advanced, and calculations put forward, which offer very strong support to the view that high solubility is an extremely desirable factor in a coke.

At the outset laboratory results show that soft coke is more readily acted upon by carbon dioxide and the oxygen in the ore than hard coke; this has been confirmed by every known investigation on the subject. The reasoning, however, that this effect is deleterious in the furnace is not so conclusive. The results obtained by Bell, and confirmed by blast-furnace managers in general, as to the deleterious effects of soft coke, do not seem to afford very strong ground for the opinion that this is due to solution losses. The authors consider that the low carbon dioxide results obtained by Bell were due not to solution loss, but to the physical action of the coke in the furnace. As a matter of fact, Bell himself supplies an explanation in this direction. In discussing the relative advantages of anthracite, coke, and charcoal in the furnace, he considers¹ that the main disadvantage of anthracite lies in the fact that it "has a tendency to splinter, thereby blocking up the air passages, and interfering with the proper access of the reducing gas to the ore."

This the authors consider is the reason for the poor results obtained with soft coke in the past. Under existing conditions of carbonisation, any soft coke produced is actually and not relatively "soft." Such coke as "black ends" and soft coke made at low temperatures in existing coke-oven plants is not nearly strong enough to stand the burden in the furnace without being crushed more or less to powder. This in itself would result in channelling, and in an uneven distribution of the reducing

¹ "Principles of the Manufacture of Iron and Steel," p. 290.

gases, with a consequent inability to act completely on the ore. There is therefore quite as much reason to attribute the deleterious results obtained with soft coke to purely physical causes as to the chemical effects of solution.

In so far as Fulton's results are concerned, the evidence advanced by him does not seem in any way to be conclusive, whilst his laboratory results were criticised by Dewey.¹ The authors therefore do not think it necessary to review this work in detail. Johnson's views, however, demand much more serious attention. It is impossible to discuss the practical work quoted by him without fuller knowledge of the conditions involved, but his theoretical calculations demand extremely careful attention. At first sight his views and assumptions seem convincing. Briefly, his opinion can be expressed as follows :

The amount of oxygen that can be imparted to the fuel in the hearth is limited by the fact that the only oxide which can exist under the temperature conditions therein is carbon monoxide. In order to convert this into CO_2 the only oxygen available is that from the ore ; therefore, if any fuel is dissolved in the upper part of the furnace, a corresponding amount of oxygen is lost at the hearth, which deficiency can never be made up, and represents a net loss of heat development when the gas is discharged from the stack.²

If this theory be correct, a solution loss of coke in the furnace, apart from its attendant thermal loss, would result in a very serious loss of fuel.

It is important to note that Johnson's calculations are based entirely upon the "critical temperature" theory. It is difficult to criticise them without knowing how far the accuracy of that hypothesis extends, and the simplest method of testing the truth of those theories would be to consider the practical results recorded in blast-furnace practice from two standpoints, viz. (1) to note the influence of fuels of high solubility on fuel consumption, and (2) to determine whether high solution loss is generally associated in furnace practice with high fuel consumption.

¹ *Transactions of the American Institute of Mining Engineers*, 1883, vol. xii. p. 111.

² Apparently, then, this reasoning would imply that the greater the blast per lb. of carbon used, the greater the economy of the furnace.—*Authors' note*.

INFLUENCE OF FUELS OF HIGH SOLUBILITY ON CARBON CONSUMPTION IN THE BLAST-FURNACE.

A considerable amount of work has been performed on the relative solubility of different fuels in carbon dioxide. Bell,¹ for example, quotes the following results :

Action of Carbon Dioxide on Different Fuels at Red Heat.

Composition of Issuing Gases.	Hard Coke.	Soft Coke.	Charcoal.
Carbon dioxide, per cent. .	94.56	69.81	35.2
Carbon monoxide, per cent. .	5.44	30.19	64.8

Action of Carbon Dioxide and Coke at Different Temperatures.

	Temperature.	Percentage of CO in Issuing Gas.
Charcoal	319° C.	0.0
„	393° C.	0.4
„	918° C.	13.0
Durham coke	332° C.	0.0
„	485° C.	0.3
„	906° C.	2.5

Similar results have been obtained with regard to the comparative power of different fuels in the direct reduction of ore by solid carbon. Invariably it has been found that the relative solubilities of the three blast-furnace fuels in general use are in the following order: (1) Charcoal; (2) coke; (3) anthracite. If, then, solubility be such a deleterious factor, it might reasonably be expected that the relative efficiencies of these fuels would be in the order: (a) Anthracite; (b) coke; (c) charcoal. Instead of this, however, charcoal in a blast-furnace invariably gives better results than coke, and coke than anthracite.

How can the superiority of charcoal as a furnace fuel be accounted for in the face of its much higher solubility? Bell's suggestion is ingenious. He states that previous ignition of both coke and charcoal greatly lessened their action on CO₂, and he advances the suggestion that "it may fairly be considered whether, after charcoal has been exposed to previous ignition in the blast-furnace . . . there is any difference between coke and charcoal in their power to resist carbon dioxide. Indeed, it seems possible that at the higher temperatures which obtain

¹ *Op. cit.*, p. 287.

in smelting iron, charcoal may be rendered less liable to attack by carbon dioxide than coke is." ¹

The authors have no hesitation in joining issue with that statement. In the blast-furnace the temperature rise is a gradual one, so that the charcoal or coke is only slowly heated to its maximum temperature. The authors have found that if coal be heated in this way, so that the temperature be only slowly increased, the coke produced is very active and possesses a high degree of combustibility and therefore of solubility in CO_2 . Further, in a blast-furnace the coke or charcoal is being heated in a stream of inert gas of constantly increasing temperature. It has been found that coal heated in this way under suitable conditions becomes converted into an activated carbon possessing an extremely high power of absorbing vapours, and with a combustibility and solubility greater than that of any blast-furnace charcoal yet produced.

Another suggestion that has been advanced is that of Foster,² that the solubility of charcoal in carbon dioxide is reduced owing to the occluded or condensed gases that it contains. This ingenious suggestion, however, does not accord with the result of experiments made with activated carbon. The capacity of this material for retaining condensed gases or vapours is considerably greater than that of ordinary charcoal. It will, for example, remove benzol completely from coal-gas, and will retain this material at temperatures considerably over its boiling point. By passing steam or other inert gas over the carbon at 300°C ., the whole of the condensed vapour can, however, be quite readily removed.

In the case of the blast-furnace, the charcoal which enters is being subjected to the action of a constant stream of inert gas of continually rising temperature, and in all probability before the charcoal reaches the zone where solution is effected, the condensed or occluded gases will have been removed and replaced by a mixture approximating in composition to the furnace gas.

Rhead and Wheeler failed to note any evidence of the condensation or occlusion of gas in charcoal heated at 400°C ., and observed that the reactivity of the charcoal towards oxygen was enormously increased by previous heating at a high

¹ *Op. cit.*, p. 289. ² *Journal of the Iron and Steel Institute*, 1904, No. I. p. 320.

temperature.¹ Professor Wheeler suggests that there is no reason why preliminary heating of charcoal should not, in a similar manner, increase the reactivity of the charcoal towards carbon dioxide; that is to say, he is in direct disagreement with Bell and with Akerman as to the preliminary heating conferring on charcoal a power of resistance to the action of carbon dioxide.²

The weight of evidence is all against the view that charcoal is protected against the action of carbon dioxide in any way whatever. This action must take place. How, then, can the low fuel consumption in charcoal furnaces be accounted for?

The question can perhaps be best answered after considering results recently obtained with modern coke furnaces working in many cases with very low fuel consumption.

EFFECT OF SOLUTION ON FUEL CONSUMPTION.

Gruner's theorem and Johnson's calculations emphasise the fact that the ideal to be aimed at is a zero solution loss; the 100 per cent. of the carbon charged should therefore be burned at the tuyeres by the blast. It is generally admitted that, as a rule, Gruner's ideal corresponds with maximum fuel economy, but Richards³ states: "If the blast be heated to a very high temperature, or particularly if it be dried, or if the ore and fuel are extra pure, so that a smaller quantity of heat is needed to melt down the slag at the tuyeres, there may not be needed at the tuyeres the generation by combustion of as much heat as Gruner's ideal working would require, and cause to be produced, and to burn all the carbon oxidised in the furnace would be wasteful of fuel. In this case, although less heat would be generated per unit of fuel by burning some of it above the tuyeres, yet economy in fuel consumption as a whole would be attained because of the *better distribution* of the heat which was generated from a smaller total quantity of fuel." "The ordinary furnace produces at the tuyeres more CO gas than is needed to abstract all the oxygen from the charge; under these conditions it is uneconomical to oxidise any carbon at all above the tuyeres.

¹ *Transactions of the Chemical Society*, 1913, vol. ciii. p. 467.

² This statement is from a private communication from Professor Wheeler to the authors.

³ "Metallurgical Calculations," p. 275.

The exceptional furnace, because of pure ores, small amount of slag, pure fuel, high temperature of blast, or dry-blast, gets heat enough at the tuyeres to melt down the charges without producing enough CO gas to reduce all the charges ; under these conditions more or less reduction is effected in quantity by solid carbon and with the greatest economy in quantity of carbon required in the furnace. These are the conditions under which, having passed the turning point, the greater economy of fuel is attained the farther away one can get from Gruner's ideal working."

Richards' theoretical conclusions are emphasised by the results quoted by Howland¹ and reproduced in Tables I., II., and III.

It is important to note that the furnaces referred to in the tables were all working with the same ores (Mesaba), and were all modern furnaces, representative of good American practice.

From the tables it can be seen that :

1. The blast per lb. of coke varied from 48.0 cubic feet to 54 cubic feet of air.
2. The proportion gasified at the tuyeres varied from 74.1 to 82.8 per cent. of the coke used.
3. There is no law governing the coke consumption and the percentage of carbon burnt at the tuyeres.
4. The lowest fuel consumption on the above list was accompanied by a solution loss of 25.2 per cent. of the total carbon charged.

On the basis of the results obtained Howland proceeded to calculate the thermal efficiencies of one of the furnaces on the following assumptions :

- A. That a proportion of the carbon was used in the direct reduction of the ore, the remaining ore being reduced by carbon monoxide, all excess carbon monoxide passing to the top gases.
- B. That all the carbon monoxide made at the tuyeres reduced the ore, and that the excess carbon was used up by carbon dioxide.
- C. That the total consumption of carbon was the same, but that it had been all burnt at the tuyeres.

¹ *Transactions of the American Institute of Mining Engineers*, 1917, vol. lvi. p. 339.

TABLE I.—(Howland.)

Kind of Coke.			Gas Analysis, Per Cent. by Volume.					Calculated Quantities, Per Ton of Iron.					Pounds Carbon, Per Ton of Iron.				Per Cent. Carbon Burned at Tuyeres.				
Furnace No.	Month and Year.	Lbs. Coke per Ton of Iron.	Tons Iron per Day.	Carbon in Coke, Per Cent.	Method of Manufacture.	Operation.	CO ₂ .	CO.	OH.	CO ₂ plus OH.	N.	H.	Lbs. Carbon to Gas.	Cub. Ft. Gas, 62° F.	Cub. Ft. Air, 62° F.	Cub. Ft. Air per Lb. Coke.	Total Charged.	Gasified in Furnace.	Gasified at Tuyeres.	Per Cent. Total Carbon.	Per Cent. Gasified Carbon.
							8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.	21.	22.
1	12/11	2615	301	86.3	BH	Stonega	10.3	27.6	0.2	38.1	59.8	2.1	2251	187,200	141,600	54.2	2254	2110	1868	82.8	88.6
2	1/12	2551	272	84.4	BP	Solva	11.3	26.9	0.6	38.8	59.0	2.2	2182	178,200	132,800	52.0	2153	2049	1179	81.4	85.6
3	1/13	2472	472	86.1	BH	Conn.	12.3	26.8	0.0	38.1	58.4	3.5	2133	177,300	131,000	53.0	2128	1996	1728	81.2	86.6
4	12/14	2247	450	87.1	BH	Conn.	11.8	26.2	0.1	38.1	58.5	3.4	1978	164,440	121,600	54.2	1957	1846	1605	82.0	87.0
5	8/14	2198	499	86.9	BH	Conn.	12.5	26.8	0.3	39.6	58.0	2.4	1933	154,600	113,200	51.6	1908	1813	1494	78.7	82.4
6	4/14	2123	541	88.3	BH	Conn.	12.8	26.0	0.2	39.0	58.0	3.0	1905	154,800	113,500	53.4	1875	1764	1498	79.8	84.9
7	11/13	2115	360	84.3	BP	Solva	14.2	25.3	0.0	39.5	57.9	2.6	1826	146,500	108,200	51.2	1782	1683	1427	80.1	84.8
8	12/14	1986	490	86.3	BP	Koppers	13.8	26.0	0.2	40.0	57.4	2.6	1718	136,100	98,800	49.5	1722	1616	1303	75.6	80.6
9	6/15	1936	376	85.7	BP	Solva	14.6	24.7	...	39.3	57.4	3.3	1689	137,000	98,900	51.1	1659	1557	1305	78.8	83.7
10	9/15	1905	393	88.7	BP	Solva	14.5	26.0	...	40.5	56.4	3.1	1700	132,900	94,900	49.8	1690	1575	1252	74.1	79.5
11	2/15	1901	517	85.5	BP	Koppers	13.6	24.9	0.2	38.5	58.0	3.2	1600	131,700	96,600	51.8	1625	1514	1274	78.4	84.1
12	11/14	1863	504	86.6	BP	Koppers	14.0	25.3	0.2	39.5	57.4	2.6	1602	128,500	90,500	50.0	1614	1513	1230	76.2	81.3
13	5/14	1780	426	84.9	BP	Koppers	14.2	26.0	...	40.2	56.2	3.6	1519	120,000	85,200	48.0	1511	1414	1124	74.4	79.5
14	10/15	1742	503	84.6	BP	Koppers	15.4	22.8	1.2	39.4	57.1	3.7	1480	119,000	85,925	49.3	1474	1382	1133	76.9	82.0
15	10/14	1716	542	87.1	BH	Benham	15.7	22.8	...	38.5	57.8	3.7	1505	123,800	93,200	54.2	1494	1396	1194	80.0	87.0
16	10/15	1715	585	84.6	BP	Koppers	15.4	22.6	1.4	39.4	57.1	3.5	1456	117,300	84,530	49.3	1451	1357	1114	76.7	82.2
17	4/14	1702	543	87.5	BP	Koppers	14.2	25.2	0.2	39.6	57.3	3.1	1476	127,500	85,600	50.3	1490	1388	1130	75.9	81.5
18	6/14	1699	572	87.0	BP	Koppers	14.9	23.5	0.2	38.6	57.3	4.1	1472	120,800	87,600	51.6	1479	1376	1155	78.2	83.9
19	2/15	1673	580	88.6	BH	Benham	15.1	23.6	...	38.7	58.6	2.8	1477	121,000	89,600	53.4	1482	1384	1182	79.9	85.0
20	1/15	1658	590	88.3	BH	Benham	15.5	22.9	0.1	38.5	58.7	2.8	1467	120,600	89,600	54.0	1464	1366	1182	80.8	86.5
21	5/15	1636	442	89.5	BP	Koppers	14.2	25.2	0.2	39.6	57.6	2.8	1464	117,100	85,200	52.0	1463	1369	1124	76.8	82.1
22	5/15	1635	593	88.5	BH	Benham	15.5	23.3	0.0	38.8	58.3	2.9	1434	117,000	85,200	52.1	1447	1349	1124	77.7	83.4
23	3/15	1624	592	87.3	BH	Benham	14.8	23.6	0.2	38.6	58.3	3.1	1401	115,000	84,800	52.2	1417	1317	1118	79.0	85.0
24	6/15	1623	457	89.6	BP	Koppers	15.3	24.8	0.2	40.3	57.0	2.7	1453	114,700	82,600	50.9	1454	1360	1090	75.0	80.2
25	4/15	1589	608	88.3	BH	Benham	15.3	23.5	0.0	38.8	58.2	3.0	1390	103,400	83,300	52.4	1403	1307	1100	78.5	84.2
26	7/15	1584	466	89.2	BP	Koppers	15.7	24.6	0.2	40.5	56.9	2.6	1423	111,300	80,100	50.6	1413	1324	1057	74.8	79.9

TABLE II.—(Howland.)

Furnace No.	Dimensions.				Capacity Cub. Ft. Tuyeres to Stock Line.	No. Tuyeres.	Date last Blown in.	Per Cent. Silicon in Iron.	Per Cent. Carbon.				Per Cent. Mois- ture in Coke.	Pounds per Ton Iron.		Engine-Room Reports.			Per Cent. Coke Screened out.	
	Heights.		Diameter.						Iron.	Stone.	Flue Dust.	Coke Dried.		Screen- ings.	Stone Used.	Flue Dust Made.	Cub. Ft. Temp. Air to Tubs. per Degs.	Grains Mois- ture.		
	Total.	Tuyeres to Top Bosh.	Hearth.	Bosh.																
1	84'	13' 4 1/2"	13'	19' 3"	14'	8	9-09	1.62	4.0	11.8	25.0	88.7	80.0	2.23	1192	225	30,040	34	1.83	0.5
2	80'	11'	11'	16'	12'	8	9-09	1.59	4.0	11.6	5.4	88.5	80.0	4.0	1148	275	25,295	...	...	0.75
3	89'	13' 10"	15' 6"	20' 6"	16'	12	9-10	2.13	4.0	12.0	11.7	88.1	...	2.25	1144	370	45,560	62	1.55	...
4	85'	13' 0"	16'	22'	16'	12	...	1.56	4.0	12.0	8.2	89.8	82.0	2.5	1097	461	44,213	82	...	0.56
5	85'	13'	16'	22'	16'	12	...	1.40	4.0	12.0	8.2	89.4	82.0	2.5	1003	388	45,839	92	6.44	0.39
6	89'	13' 10"	15' 6"	20' 6"	16'	12	9-10	1.93	4.0	11.7	12.0	90.7	80.0	2.25	1208	180	46,090	52	3.15	0.5
7	80'	12' 11"	12'	18' 6"	13' 6"	8	9-12	1.53	4.0	12.05	11.6	89.1	81.5	4.00	1190	116	32,380	70	4.28	1.5
8	94'	11' 7"	17'	21' 3"	16' 3"	12	2-14	1.03	4.2	11.75	9.0	88.5	...	2.50	870	140	39,210	38	1.05	...
9	80'	11' 11"	13' 6"	18' 6"	14'	8	5-15	0.94	4.1	12.05	4.8	89.4	84.0	3.85	1101	224	30,799	90	5.9	0.3
10	80'	11' 11"	13' 6"	18' 6"	14'	8	5-15	1.26	4.4	12.0	8.5	91.6	84.0	2.9	1042	192	31,120	85	6.6	0.3
11	Same as No. 8						0.90	4.25	11.93	11.45	88.3	...	3.07	719	140	36,824	37	2.58	...	
12	Same as No. 8						0.95	4.20	11.75	7.55	88.85	...	2.50	755	98	38,220	54	2.04	...	
13	78'	19' 10"	14'	19' 6"	15'	9	3-14	1.26	4.00	11.70	...	88.00	...	3.50	897	60	29,670	62	...	...
14	85'	14' 3"	15'	20' 6"	15' 5"	12	1-15	1.00	4.00	12.00	2.00	89.1	87.0	4.32	828	135	36,368	60	4.0	1.7
15	90'	14'	16' 6"	21' 6"	16'	12	9-14	1.62	4.00	12.00	10.0	92.0	80.0	1.55	912	89	35,385	65	...	3.2
16	90'	14' 3"	16' 6"	21' 4"	16' 6"	12	9-13	0.89	4.00	12.00	2.1	89.1	87.0	4.32	833	200	42,765	60	3.9	1.6
17	90'	14' 6"	17' 8"	22'	17'	10	2-14	1.23	4.20	11.75	6.2	89.5	...	2.25	752	95	42,950	49	2.5	...
18	Same as No. 17						1.35	4.20	11.75	8.25	89.0	...	2.30	804	82	48,978	75	5.5	...	
19	Same as No. 15						1.56	4.00	12.00	9.5	93.3	80.0	1.85	780	94	55,615	62	2.2	3.8	
20	Same as No. 15						1.41	4.00	11.9	9.1	92.6	80.0	2.23	849	90	35,820	62	1.7	2.8	
21	Same as No. 13						1.36	4.1	12.0	4.8	91.8	...	2.5	792	31	30,050	70	3.8	...	
22	Same as No. 15						1.62	4.0	11.9	8.0	92.2	80.0	1.4	709	99	35,210	56	3.8	3.0	
23	Same as No. 15						1.48	4.0	11.7	8.8	91.2	80.0	1.6	714	125	35,680	62	1.8	3.0	
24	Same as No. 13						1.19	4.1	12.0	6.9	91.9	...	2.5	775	...	29,910	75	5.0	...	
25	Same as No. 15						1.67	4.0	11.7	7.1	92.3	80.0	1.5	712	94	35,570	62	3.4	3.3	
26	Same as No. 13						1.20	4.1	12.0	7.6	91.5	...	2.5	828	...	30,210	80	6.4	...	

Cases A and B correspond with solution loss either by direct reduction or by solution in the carbon dioxide, whilst the third assumption corresponded to Gruner's ideal.

The results of these calculations are shown in the following table :

TABLE III.—*Use of Carbon under Various Assumptions.*
(Howland.)

Per ton iron = 2240 lbs.

	Wisconsin Furnace No. 1.		
	"A."	"B."	"C."
1. Coke, pounds	1673	1673	1673
2. Carbon charged, pounds	1482	1482	1482
3. Carbon gasified, pounds	1384	1384	1384
4. Carbon reduction Mn, P, Si, pounds	36	36	36
5. Carbon direct reduction Fe_2O_3 , pounds	166	41	0
6. Carbon indirect reduction Fe_2O_3 , pounds	807	1182	1304
7. Carbon in CO not needed for reduction, pounds	375	0	44
8. Carbon dissolved by CO_2 , pounds	0	125	0
9. Carbon gasified at tuyeres, pounds	1182	1182	1348
10. Carbon used in reducing Fe_2O_3 , pounds	973	1223	1304
11. Cubic feet air per pound coke, 62°F	53.4	53.4	61.08
12. Analysis of top gas . . . . .	...	...	...
13. CO per cent. by volume, per cent.	23.6	23.6	17.7
14. CO_2 per cent. by volume, per cent.	15.1	15.1	18.0
15. H per cent. by volume, per cent.	2.7	2.7	2.7
16. N per cent. by volume, per cent.	58.6	58.6	61.6
17. Total B.Th.U. per cubic feet top gas at 62°	84.0	84.0	64.8
18. Cubic feet gas per ton iron	121,000	121,000	131,200
19. B.Th.U. per pound C gasified	7344	7344	6143
20. B.Th.U. in CO per cubic foot top gas	76.6	76.6	57.4
21. B.Th.U. in CO per pound carbon gasified	6697	6697	5441
22. B.Th.U. lost to top gas per pound carbon gasified . . . . .	...	...	1256

It is evident that if Gruner's ideal had been adhered to the net result would have been a considerable reduction in efficiency.

In conclusion Howland states : "... Low coke consumption goes hand in hand with low wind. ... The lower volume of gas means, in a hearth of a given area, a lower velocity of the gases, thus tending to concentration of heat." Low wind is, of course, indicative of high solution loss, and apparently then high solution loss is accompanied in favourable cases by low fuel consumption.

The above particulars, together with results obtained with charcoal furnaces, all point in the same direction, namely, that far from being a deleterious property, a high solubility factor in a coke is a most important asset in securing a low fuel consumption. This conclusion receives considerable emphasis if the question be examined from a slightly different standpoint.

COMBUSTIBILITY—THE MOST IMPORTANT PROPERTY IN A COKE.

The solubility of a coke is in itself a measure of its combustibility. The most accurate and probably the simplest method of determining the reactivity of a coke is to make actual measurements of the rate at which it combines with oxygen under standard conditions at a given temperature, say $400^{\circ}\text{C}.$, and the rate at which carbon dioxide is reduced by it at a given temperature, say $900^{\circ}\text{C}.$ A note on this subject, with a record of some of the results obtained with different fuels, is given as an addendum to this paper by Professor R. V. Wheeler.

The conception of combustibility as a factor in blast-furnace practice is not altogether new. It does not play a very important part in Bell's writings. He devotes a great deal of time to the question of solution, but the nearest approach by him to the idea of combustibility of a fuel influencing blast-furnace results is perhaps contained in the conclusion that he was forced to arrive at in his endeavours to explain the reasons for the high thermal efficiencies of charcoal furnaces as compared with coke furnaces. This is, that "the circumstances attending the combustion of charcoal differ from those of coke."¹

Contemporaries and predecessors of Bell, however, devoted a fair amount of attention to this question, and this was especially true in cases where they had personal experience of charcoal furnaces. A study of some of the older literature of this period, when charcoal was still extensively used as a furnace fuel, makes very interesting reading. Percy,² for example, quotes a number of experiments that had been performed chiefly by Violette with reference to the combustibility of charcoal prepared at various temperatures; the lower the temperature of carbonisa-

¹ Bell, *op. cit.*, p. 282.

² "Fuel," p. 359.

tion, the higher the combustibility. Further,¹ he quotes the economies obtained in melting iron with imperfectly burnt charcoal ("charbon roux"). Work on this particular question had been performed as far back as 1835, and some of the earlier American writers also laid emphasis on this fact.² It was the general opinion in American charcoal practice of that period (1875-80), that the use of imperfectly burnt charcoal was always attended by the maximum of fuel economy.

Further, it was well known that charcoal gave much better results in the blast-furnace than either coke or anthracite. In the paper already referred to, Church³ went in detail into the cause of the superiority of charcoal. He gave two view-points as to the reason for this: (1) the scientific view-point represented by the theories of Akerman, and (2) the practical view-point. Akerman and his school had contended that charcoal—owing to its high porosity—reduced the carbon dioxide more rapidly than either coke or anthracite. At that time it was considered that carbon dioxide was the first product of combustion, this being subsequently reduced to carbon monoxide, a theory exploded by the work of Wheeler and his collaborators. Practical men, on the other hand, considered that the low consumption of charcoal in the furnace was due to its higher rate of combustion, resulting in a higher temperature in the hearth. Church considered both explanations—the practical and the scientific—to be fallacious. A correct theory would have to be in agreement with the practical observations that (a) for a given weight of fuel, the well of a charcoal furnace was hotter than that of a coke furnace, and (b) that more fuel reached the hearth of an anthracite furnace than that of a coke furnace.

The highest carbon duty was given by a fuel which withdrew most of the oxygen from the blast in a given space of time; or, in other words, the duty was proportional to capacity for combustion in extremely dilute oxygen. As long as the oxygen percentage in the blast remained within certain limits fuel of any kind would take it up easily, but when that oxygen was reduced to about 10 per cent. (the limit when flame was extinguished is oxygen

¹ "Fuel," p. 409.

² Church, *Transactions of the American Institute of Mining Engineers*, 1875, vol. iv. p. 119; Fernow, vol. vi. p. 199; and Kent, vol. vi. p. 206.

³ *Transactions of the American Institute of Mining Engineers*, 1878, vol. vii. p. 33.

10 per cent., carbon dioxide 8 to 10 per cent.) the fuel which combined with it more rapidly was the superior. With a fuel of low combustibility, free oxygen was carried to the boshes to be consumed away from the zone of highest temperature, thus necessitating an increased fuel consumption to maintain the necessary heat at the hearth.

The question was later followed up by Thorner,¹ who made a detailed investigation on a number of blast-furnace fuels consisting of several varieties of coke, charcoal, and anthracite, and determined their actual specific gravities, porosity, strength under compression, rate of solubility in carbon dioxide, and combustibility in air. He also made microscopic examination of sections of these fuels, with a view to determining the influences of their structure upon the above properties. His results can be summarised in Table IV. Taking a general view of Thorner's work in so far as it concerns the blast-furnace, his opinion can be summarised as follows:

1. The best results in blast-furnace practice were obtained with Meiler coke and with charcoal—both fuels possessing the following characteristics: (a) High proportion of volatile matter; (b) high degree of solubility in CO_2 ; (c) high degree of combustibility in air.

2. The inferior results obtained with coke in the blast-furnace could be improved by modifying the coke so as to convert the basic substances into an easily oxidisable modification.

3. The ideal blast-furnace fuel should be as similar to charcoal as possible.

Owing probably to the influence of Bell, and the indifference displayed by him to the importance of combustibility, very little work appears to have been done on the subject subsequent to the above until within comparatively recent years. In 1914 a paper was read by Brassert, "On Coke, with Particular Reference to Combustibility." This is reproduced in full by Johnson,² who points out that the value of the coke in relation to the heat reactions in the furnace is determined not only by its carbon content, but even more so by its combustibility. He still, how-

¹ "Contribution to the Study of Coal, Coke, and Charcoal as Fuels for Blast-Furnaces," *Stahl und Eisen*, 1886, vol. vi. p. 71.

² J. E. Johnson, *op. cit.*, p. 171.

ever, considered that high solubility in CO_2 was deleterious, and his ideal coke was one which would burn rapidly at the tuyeres and yet not be too vulnerable to the ascending gases. The

TABLE IV.—(Thorner.)

Class of Coal.	Ash.	Specific Gravity.		Porosity 100 Grms. Fuel Content.		Organic Volatile Matter.	Loss in CO_2 in Half Hour.		Loss in Blast in Ten Minutes.	
		Apparent.	Actual.	Vol. of Pores.	Vol. of Substance.		Per Cent.	Per Cent.		
					CO_2 .					CO .
1. Retort coke	3.8	0.858	1.825	61.6	54.8	...	10.6	46.8		
2. Gas	7.5	0.868	1.811	60.0	55.2	0.25	11.8	45.0		
3. Pressed	7.7	0.984	1.852	47.6	54.0	1.4	...	51.0		
4. " "	6.9	0.969	1.786	47.2	56.0	1.15	13.8	48.9		
5. Coppee	7.99	0.926	1.880	54.8	53.2	1.13	8.4	50.1		
6. " "	7.8	0.909	1.825	55.8	54.8	1.55	8.7	54.4		
7. " "	7.3	0.890	1.852	58.4	54.0	1.70	8.3	51.5		
8. " "	10.6	0.919	1.852	54.8	54.0	...	9.5	46.8		
9. " "	8.8	0.874	1.852	60.4	54.0	0.75	12.2	57.1		
10. " "	8.45	0.89	1.894	59.6	52.8	...	6.8	52.1		
11. " "	7.6	0.903	1.909	58.4	52.4	...	8.9	52.5		
12. " "	7.6	0.989	1.887	49.0	53.0	...	45.6	87.7		
13. Meiler	2.9?	1.046	1.488	28.4	67.2	29.7	...	100.0		
14. Pine charcoal	2.8	0.382	1.626	200.4	61.6	29.7	85.0	78.6		
15. Oak	2.45	0.597	1.347	96.2	74.2	17.9	...	80.3		
16. Beech	2.10	0.594	1.481	100.8	67.6	13.2	95.0	100.0		
17. " "	1.65	0.484	1.351	132.5	74.6	11.8	95.0	100.0		
18. Anthracite	9.3	1.572	1.666	3.6	60.0	13.2	95.0	45.4		

Microscopic Examination.

1. Large pores, thick pore walls.
- 2 and 4. Many very small pores.
- 5, 6, 7, 8. Less small and big pores.
9. Numerous small and many big pores.
10. Small and large pores.
- 11 and 12. Very large pores.
13. Numerous small pores with pronounced tendency in longitudinal direction.
14. Numerous microscopic small regularly arranged cells of tabular form.
15. Fewer and larger pores.
16. Like pine charcoal but larger cells.

combustibility of a coke was influenced by (1) its size, (2) the physical and chemical conditions of the cell wall substance, (3) the interior and surface cell structure of the coke pieces, (4) the character of the coal used, (5) the method of carbonisation adopted, (6) the speed of carbonisation, (7) the method of

quenching, and (8) the method of screening and handling. This very brief summary gives an excellent idea of the factors involved in attaining a high degree of combustibility when ordinary methods of coking are adopted.

Howland, in the paper already referred to, emphasises the importance of the factor of combustibility in a coke, and stated that "the most desirable thing about a coke is that quality in the carbon which will allow of it being instantaneously burned to CO, and thus result in the maximum concentration of heat where needed." Later, Koppers,¹ in a paper read to the Blast-Furnace Committee of the German Iron and Steel Makers, developed the idea of combustibility to a considerably greater extent than had been done hitherto. One of the most important effects produced, in his opinion, was the reduction in the extent of the oxidising zone near the tuyeres.

Professor Wüst had shown some years before that a strongly oxidising zone existed near the tuyeres. Under the influence of free oxygen and of carbon dioxide—which at high temperatures is a powerful oxidising agent—a proportion of the iron became oxidised. This necessitates a further supply of carbon for its direct reduction, resulting in the following series of cumulative effects: (1) Higher coke consumption; (2) greater blast; (3) greater heat for blast; (4) greater load on engines; (5) lower production of iron.

A combustible coke offered the following advantages: (1) Reduction in area of oxidising zone at tuyeres. (2) Better iron. He pointed out that in charcoal iron, carbon segregates out in minute leaves of graphite, whilst with coke the graphite in the pig separates as large leaves. The more combustible the coke the more nearly does the iron approach the quality of charcoal iron. There is also less ferrous oxide in the pig. (3) Desulphurisation in the iron is effected better by combustible coke, owing to the reduced oxidising zone, less FeO goes into the slag, which is therefore better able to absorb sulphur.

He suggested that modifications in the existing methods of coke manufacture should be adopted in order to increase the combustibility of the fuel for blast-furnace purposes.

The authors have worked upon this question from a rather novel standpoint, but before proceeding to discuss their views

¹ *Stahl und Eisen*, August 25, 1921, vol. xli.

it might be of some interest briefly to outline the factors involved in the rapid combustion of coke in a blast-furnace.

FACTORS INFLUENCING RAPID COMBUSTION OF FUEL IN A BLAST-FURNACE.

This question was recently dealt with from a mathematical standpoint by Korevaar.¹ Essentially the rapidity of combustion in a blast-furnace was dependent on the following factors :

1. Blast-furnace factors. Dimensions of the furnace—shape—character of material of which it is built, &c.
2. Factors depending on the fuel :
 - (1) Activity (or combustibility).
 - (2) Porosity.
 - (3) Size of the fuel particles.
3. Factors depending on the blast :
 - (1) Velocity.
 - (2) Temperature.
 - (3) Concentration of oxygen.
 - (4) Proportion of water vapour.

FACTORS DEPENDING ON THE FUEL.

Activity of the Fuel.

1. With a very active fuel, or when the temperature is very high, combustion takes place in a zone of very small volume.

2. With a less active fuel or with lower temperature, the combustion zone is greater in volume.

3. With a poorly active fuel or low temperature, the combustion zone is still larger, and some of the oxygen may leave the combustion zone unattacked.

The value of the zone of combustion can be represented mathematically by the following equation :

$$O = \frac{2O_k r_k}{2 \cdot 2215r \cdot P} = \text{volume of zone combustion.}$$

Where O = volume of combustion zone ;
 r_k = average radius of carbon particles (assumed to be spherical) ;
 O_k = total surface of zone ;
 P = factor depending on porosity of coke ;
 r = radius of combustion zone.

¹ *Chimie et Industrie*, vol. viii. No. 1, July 1922.

This equation gives the relationship between the volume of the zone of combustion and the different factors depending on the fuel ($O_k r_k \div P$). The factor r , depending on the furnace, remains constant.

With an active carbon the surface of combustion O_k remains small, so that this factor can serve as a factor of activity. With small particles of carbon r_k becomes small, therefore O diminishes, and with high porosity factor the same thing applies.

RELATION BETWEEN VOLUME AND TEMPERATURE OF COMBUSTION ZONE.

Korevaar calculates that in a gas-producer working under stable conditions with pure carbon :

$$O = \frac{417 (0.24t - 0.228T)}{K (T - T_o)} \times \text{kilogramme of carbon burnt per minute.}$$

Where t = temperature of blast ;

T = temperature of combustion zone ;

K = a constant depending on furnace ;

T_o = external temperature.

From this it will be seen that the volume of the combustion zone decreases as the temperature increases, and *vice versa*. If O , the volume of the combustion zone, becomes infinitely small (zero), T would become 1875° —the maximum temperature obtainable with cold air. As, however, O cannot become infinitely small, the maximum temperature will be somewhat lower than this.

In blast-furnace practice Korevaar's mathematical demonstration shows that :

1. The temperature of the combustion zone can be increased by the employment of a more active fuel.
2. With a more active fuel the necessary temperature can be obtained with a lower fuel consumption.
3. Assuming the temperature of the combustion zone to be constant, the employment of a more active fuel diminishes the volume of the zone of combustion.
4. An increase in blast temperature allows the critical temperature to be obtained with a low fuel consumption.
5. The lowest fuel consumption is obtained by the lowest possible air velocity at the tuyeres, taking into consideration the activity of the fuel and the temperature of the blast. (Compare

Howland, "Low coke consumption goes hand in hand with low wind.")

This exposition develops mathematically the contention elaborated in a qualitative manner by Koppers with reference to the influence exerted by the fuel activity on the volume of the oxidising zone, and also explains to some extent the views of Howland.

There is one other theoretical question that needs to be touched upon. Oxidation of the iron in the vicinity of the tuyeres can be effected either by free oxygen or by carbon dioxide.

INFLUENCE OF FUEL ACTIVITY ON THE PROPORTION OF CO_2 PRODUCED AT THE TUYERES.

The researches of Rhead and Wheeler¹ on the combustion of carbon have shown that :

- (1) When carbon burns, both carbon dioxide and carbon monoxide are produced simultaneously.
- (2) When carbon burns, it first forms a complex with oxygen, which is afterwards decomposed to a mixture of carbon monoxide and carbon dioxide.
- (3) The fixation of oxygen is affected considerably by the "activity" of the carbon (graphite is not affected to the extent that charcoal is), and great care had to be taken in the experiments to obtain a "normal" condition of activity at the outset.
- (4) The ratio $\text{CO}:\text{CO}_2$ in the products of combustion increased from 400° to 600° ; diminished from 600° to 850° , and then rapidly increased.
- (5) Above 750° the rate of reaction $\text{CO}_2 + \text{C} = 2\text{CO}$ becomes appreciable, the quantity of carbon dioxide reduced depending largely on the length of time it is allowed to remain in contact with the carbon.
- (6) Reduction of carbon dioxide becomes very rapid above 1000°C . (a study of the curves obtained by these writers indicates that at the high temperature existing in the blast-furnace the production of carbon dioxide would be extremely small).

¹ *Transactions of the Chemical Society*, 1912, vol. 101, p. 831; 1912, vol. 101, p. 846; 1913, vol. 103, p. 461.

In all probability carbon dioxide would only be present in the hearth in the zone where free oxygen also exists, so that any method of reducing this zone would at the same time reduce the possibility of contact of the iron with the oxidising carbon dioxide. In any event, the higher the temperature in the hearth, the smaller the possibility of carbon dioxide being present. As an active fuel results in an increased temperature and a smaller zone of combustion, the zone in which carbon dioxide is likely to be present is diminished, and thus the liability of the iron sponge to reoxidation is reduced.

METHODS OF PRODUCING AN "ACTIVE FUEL."

The authors' work with reference to the production of an active fuel has developed upon somewhat novel lines. Their views regarding the theoretical aspects of the question were recently presented in a paper to the Society of Chemical Industry.¹ They found that the combustibility of a carbonised fuel is primarily dependent not so much on the percentage of volatile matter it contains as upon its structure. Provided care be taken to obtain a certain characteristic structure in the resulting product, a coal can be carbonised at practically any temperature, in practically any type of carbonising system, and still retain an extremely high degree of combustibility.

The factors involved in the production of this structure can be summarised as follows :

(A) Preparation of the coal prior to carbonisation :

- (1) Efficient cleaning.
- (2) Preliminary treatment or blending of coals or coke to ensure a minimum of swelling in the retort.
- (3) Fine grinding of the coal.
- (4) Briquetting of finely divided coal mixture.

(B) Carbonisation of the coal as slowly as possible consistent with economic requirements.

The general methods adopted to effect these results have been outlined in a paper by the authors to the South Wales Institute of Engineers.² The characteristics of the structure

¹ *Journal of the Society of Chemical Industry*, June 1922, vol. xli. pp. 196T-208T.

² *Proceedings of the South Wales Institute of Engineers*, July 1922, vol. xxxviii. p. 341.

of the resulting fuel can be summarised as follows : (1) Extensive area of surface per unit of mass. (2) High porosity. (3) Minute size of cells. (4) Pronounced porosity of cell walls. (5) Greater degree of continuity of cell structure than is the case with ordinary blast-furnace coke.

The accompanying photomicrographs (Plates I. and II.), taken by Sir George Beilby, and reproduced by his kind permission from a paper by him to the Society of Chemical Industry,¹ give an indication of the difference in structure existing between different types of coke. In this paper Beilby expressed the opinion that the ultimate coke substance is in every case—from wood charcoal to coke—of a vitreous character—"it is a true glass"—and that the main factors in the production of a reactive coke area are :

- (1) The area of the reactive surface in the coke.
- (2) This is influenced by the size of the cells and the thickness of the cell walls—the more minute the cells and the thinner the cell walls, the greater the area of reactive surface.
- (3) The accessibility of the reacting gases to the interior of the coke mass.

The whole subject, from a theoretical standpoint, is extremely fascinating, and opens up a field of immense possibilities not only in the fuel and iron and steel industries, but in practically every sphere of chemical and metallurgical practice. For the moment, however, all that it is necessary to say is that by suitable methods of treatment a fuel can be obtained of hardness equal to that of metallurgical coke, of density approaching that of coal, and with a combustibility or "reactivity" of the order of that of charcoal.

The following particulars of such a fuel may be of interest :

Analysis of "Pure Coal Briquette" Coke.

	Per Cent.
Ash	8.0
Volatile matter	0.75
Apparent specific gravity	1.20
True specific gravity	1.80
Volume of cells	33.3

These results, together with those submitted by Professor Wheeler and his collaborators at the end of this paper, show

¹ *Journal of the Society of Chemical Industry*, 1922, vol. xli., No. 21, pp. 341T-347T.

that a material prepared in the manner outlined possesses the properties both of coke and charcoal (differing, however, in the very high apparent specific gravity that it possesses). The authors venture to believe that the use of a fuel of this character will allow of considerable economies being effected in the fuel consumption of blast-furnaces.

This view, of course, is based as yet purely upon theoretical considerations, and pending a large scale trial it is impossible to say how far they are correct or not. It might, however, be of interest to outline some of the theoretical considerations which point in this direction. In view of the similarity of reactive coke to charcoal, it is advisable to examine the behaviour of charcoal in the blast-furnace.

BEHAVIOUR OF CHARCOAL IN THE BLAST-FURNACE.

The behaviour of charcoal in the blast-furnace differs very considerably from that of coke, and some of the most important points of difference can be outlined as follows :

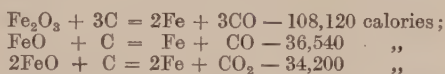
TABLE V. (*from Bell*).
Temperatures in Coke and Charcoal Furnaces.

Height from Tuyeres in Feet.	Temperature. Degrees C.		Coke Furnace 45 Feet High.	Height from Tuyeres in Feet.
	Coke.	Charcoal.		
70	335	...	...	70
65	455	...	...	65
60	540	...	...	60
55	650	...	...	55
50	825	...	...	50
45	925	...	400	45
40	980	...	455	40
			650	
35	...	90	825	35
		160	925	
30	1010	340	...	30
		550	980	
25	...	640	1010	25
		680		
20	...	...	...	20 °
15	...	840	...	15
		910		
10	...	950	...	10
		1150		
5	...	...	...	5
Tuyeres	...	...	...	Tuyeres

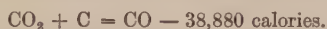
1. The temperature gradient in a charcoal furnace differs from that of a coke furnace. Table V., adapted from particulars given by Bell,¹ gives the temperatures observed in two coke blast-furnaces 72 and 48 feet high, and in a charcoal blast-furnace 35 feet high.

The temperature in the charcoal furnace falls rapidly within a distance of only 15 feet from the tuyeres, and this points to powerful endothermic reactions in that zone. These may be due to :

- (1) The dissociation of limestone and evolution of CO₂.
- (2) The direct reduction of oxide of iron according to the equations—



or (3) The solution of carbon in carbon dioxide—



The drop in temperature from a point 15 feet above the tuyeres to the outlet is such as approximates to balance the heat absorbed by the incoming burden. It may be assumed that little chemical reaction takes place above this point.

2. The process of reduction in a charcoal furnace differs from that of a coke furnace. In a coke furnace the greater proportion of the ore is reduced within a distance of 25 feet of the throat.² In a charcoal furnace, working with low fuel consumption, the greater proportion of the ore is reduced in the lower reducing zone near the tuyeres. Ebelman has shown that with charcoal furnaces the ore might reach the hearth containing 50 per cent. of ferrous oxide.

3. The passage of the ore through the furnace is much more rapid than with a coke furnace. In one case referred to by Bell the ore in a coke furnace took a period of twelve hours to travel a distance of 15 feet, whilst in a charcoal furnace quoted it travels half the height of the furnace in one hour.

4. Appreciable quantities of carbon dioxide are found in every portion of the furnace, whilst in the case of a coke furnace

¹ "Principles of the Manufacture of Iron and Steel," pp. 72 and 295.

² *Op. cit.*, pp. 219-2 and 295.

very little additional carbon dioxide is found below the zone of limestone decomposition until the vicinity of the tuyeres is reached.

5. The output per cubic capacity of a charcoal furnace is generally higher than that of a coke furnace.

6. Less carbon deposition occurs in a charcoal furnace than in a coke furnace.

Reviewing generally the work done in the charcoal furnace, it appears that there is a far greater difference between the behaviour of charcoal and coke than would be accounted for by the difference in chemical composition (sulphur, ash contents, &c.). The difference is one primarily connected with the reactivity of charcoal compared with coke. This results in the following series of consequences :

- (1) Consumption at the tuyeres can be effected more rapidly.
- (2) Rapid lowering of the burden.
- (3) Reduction is delayed.
- (4) Larger proportion of direct reduction in the lower reducing zone near the tuyeres.
- (5) More reduction may be thrown on the hearth without derangement.
- (6) Greater solution.

Solution, however, is not attended with any serious loss to the efficiency of the furnace, as was shown by Howland's analysis. Solution takes place principally in two zones, viz. : (1) The zone of limestone decomposition, and (2) the lower reducing zone near the hearth.

Any carbon monoxide given off as the result of the action of carbon dioxide on carbon in the zone of limestone decomposition is still at such a temperature as to be able to effect reduction of the ore lying above it, whilst the carbon monoxide produced by solution in the hearth is at such a temperature as to be equivalent in reducing power to gas produced by combustion. This is shown by the analysis given later.

There is one point which has important consequences, and that is that carbon deposition is less pronounced in charcoal furnaces than in coke furnaces. In a furnace where reduction takes place at a temperature of 400° to 500° C. carbon deposition

is greatly facilitated; this action results in the evolution of heat, due to the reaction, $2\text{CO} = \text{C} + \text{CO}_2 + 38,880$ calories, and this, combined with the heat released by the reaction of $\text{Fe}_2\text{O}_3 + 3\text{CO} = 2\text{Fe} + 3\text{CO}_2 + 8520$ calories, further tends to induce the reduction of the burden in the upper reaches of the furnace; in short, these reactions are self-supporting in regard to heat development, and the height of a furnace could be increased indefinitely without stopping it.

The heat released in this way is largely lost to the furnace, being expended in heating up the furnace gases and increasing the loss due to radiation. It is true that the deposited carbon is returned to the furnace subject to such loss as passes away in the flue dust, but the carbon has the serious effect of splitting up the ore into powder and impeding the free passage of the gases, and the reduced iron reaches the melting zone surrounded with fine carbon, which seriously impedes the coalescence of the iron globules as they melt. It also acts as a non-conducting material, preventing rapid heating up of the burden. It does assist, however, to some extent to carburise the iron. On the other hand, where the reduction takes place, as in a charcoal furnace, principally at a high temperature from 850° to 1000°C. , the tendency to deposit carbon is much less pronounced and the ore is reduced in lump form, which offers less resistance to the blast and melts far more readily.

The effect of deposited carbon is therefore to produce a loss of heat, and is one of the reasons for a coke furnace requiring a hotter zone for the final heating and melting of the charge.

After the above review of the conditions in a charcoal furnace, it might be possible to outline the special characteristics of a reactive fuel in the blast-furnace. It would differ to some extent in its action from charcoal, owing to the difference in its properties.

DIFFERENCES BETWEEN REACTIVE COKE AND CHARCOAL.

The apparent specific gravity of the coke is much greater than that of charcoal. It is, in fact, greater than that of ordinary coke. This would have the following consequences:

- (a) The space occupied by the ore and the limestone would be considerably increased.

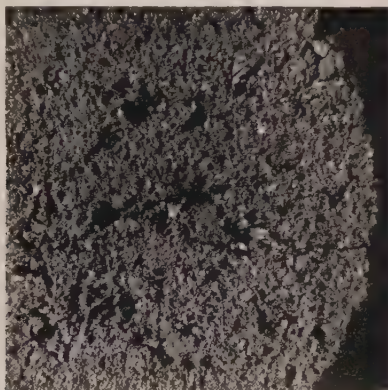
- (b) The period of contact of the reducing gases with ore and limestone would be much greater than in a charcoal furnace.
- (c) Whilst this coke might be burned at the tuyeres as rapidly as charcoal, yet the volume occupied by the coke would only be about half that occupied by charcoal, so that the burden would not be lowered so rapidly as is the case in a charcoal furnace.
- (d) Owing to the greater mass of fuel per unit of volume occupied, the zone of oxidation at the tuyeres would probably be less than is the case with charcoal.
- (e) The combined effect of these differences would probably result in an economy of fuel as compared with charcoal, due to the following causes :
 - (1) The smaller oxidising zone at the tuyeres would reduce the secondary oxidation of the spongy iron, with its consequent waste of fuel.
 - (2) From Korevaar's equation, the smaller oxidising zone would be accompanied by a hotter hearth than is the case with charcoal.
 - (3) Reactive coke is much harder than charcoal. There would probably therefore be less breakage, less channelling, and a more even distribution of the reducing gases in the furnace.
 - (4) Furnaces using coke can be built of much greater capacity than is the case with charcoal, thus allowing increased blast temperature, and resulting in reduced radiation and other furnace losses per unit of iron produced.
 - (5) Against these advantages, however, would be the increased ash and sulphur in the fuel as compared with charcoal. The increased fuel consumption due to these impurities can, however, be calculated, and on the balance theory points to the view that the economies would outweigh the losses.



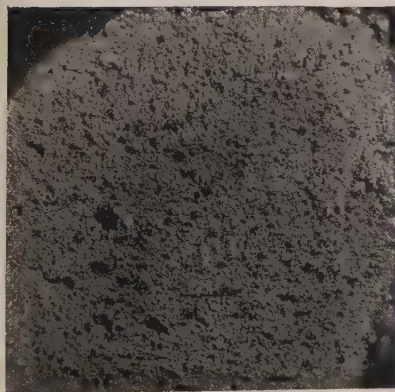
No. 1. Gas Coke made in horizontal retorts from Durham coal (Beilby).



No. 2. Blast-furnace Coke from recovery ovens (Beilby).



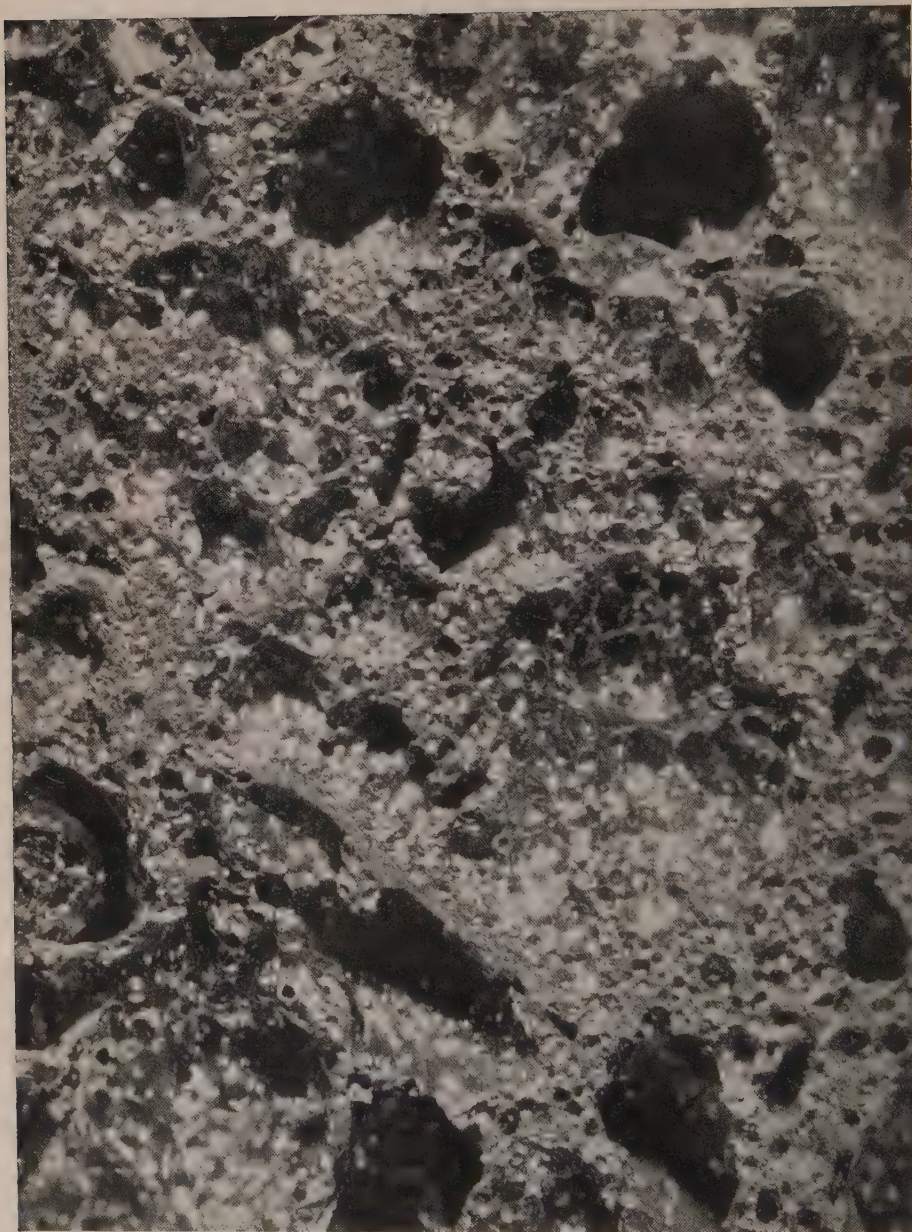
No. 3. Laboratory Assay Coke from Dalton Main coal.—Fuel Research Board (Beilby).



No. 4. Coke made from coal briquetted without binder (Beilby).



No. 5. Coke made from mixture of caking and non-caking coals briquetted without binder (Beilby).



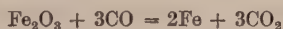
No. 6. Enlarged micro-photograph of Gas Coke made in vertical retorts (Beilby).

CHARACTERISTICS OF A REACTIVE COKE IN A BLAST-FURNACE.

One of the most important features of a reactive coke would be the effect it would have, in common with charcoal, of lowering the zone of reduction in the furnace, thus enabling the furnace reactions to be carried out at a much higher temperature than is the case with an ordinary coke. In fact with a reactive fuel there is every probability that a larger proportion of reduction would be effected in the hearth than is the case with ordinary coke, with corresponding economy of fuel.

Let us consider the reactions taking place in a furnace operating like a charcoal furnace, in which a large proportion of the reduction takes place at a high temperature. There is one important feature in this connection which is not generally realised, and that is that the reducing reactions at a high temperature give out considerably more heat than at a low temperature. Thus :

At 900° C. the reaction



gives out 21,695 calories as against 8520 calories at ordinary temperatures.¹

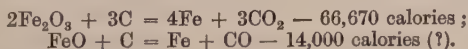
At 830° C. the reaction



gives out 8724 calories as against a *heat absorption* at 580° C. of 3100 calories.²

On the other hand, the following heat-absorbing reactions can take place, viz. :

At 900° C.



The latter reaction is accompanied at ordinary temperatures by a heat absorption of 29,060 calories. The specific heat of ferrous oxide is not known at high temperatures, but on the assumption that it was similar to that of ferric oxide the heat absorption at 900° C. would be only 14,000 calories.

¹ Richards, "Metallurgical Calculations," p. 128.

² Mahler, *Journal of the Iron and Steel Institute*, 1905, No. I. p. 645. *Revue de Métallurgie*, 1904, vol. i. p. 493.

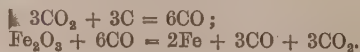
It is evident that the heat-producing reactions, once started, proceed with greatly increased rapidity as the temperature rises, and once they commence at high temperatures, given the necessary supply of CO from the hearth, they go on to completion giving out heat, and if there were no other reactions of an opposite nature, the temperature of this part of the furnace would go on increasing. The heat produced, however, finds utilisation in facilitating the heat-absorbing reactions in such a way as to promote the attainment of balance between all the reactions in this zone.¹

From observations made in a charcoal furnace this balance between the opposing reactions would be obtained at 850° C., when the carbon monoxide and carbon dioxide are approximately in equal proportions.

Assume that the reduction of ferric oxide proceeds thus: $\text{Fe}_2\text{O}_3 + 2\text{CO} = 2\text{FeO} + \text{CO} + \text{CO}_2$, and that the resulting ferrous oxide is reduced by solid carbon according to the equation, $2\text{FeO} + 2\text{C} = 2\text{Fe} + 2\text{CO}$. Since the carbon monoxide produced by the latter reaction is utilised in reducing ferric oxide, then, in effect, reduction of two atoms of iron have been effected by two atoms of carbon, which is perhaps the minimum carbon consumption for the reduction of ferric oxide, and is equivalent to 4.28 units of carbon for 20 units of iron.

If, however, we first burn carbon at the tuyeres thus: $6\text{C} + 3\text{O}_2 = 6\text{CO}$, and use these six molecules of carbon monoxide thus: $\text{Fe}_2\text{O}_3 + 6\text{CO} = 2\text{Fe} + 3\text{CO} + 3\text{CO}_2$, it has taken exactly three times as much carbon, or an equivalent of 12.84 units per 20 units of iron and given out 8520 calories. If, therefore, we can utilise the heat generated in the latter reaction to facilitate the former, a distinct gain in economy is effected.

It is not absolutely necessary for direct reduction to take place; the same ultimate results can be obtained by intermediary action of carbon dioxide thus:



¹ The term "balance" is used advisedly, in order that it may not be confused with the conception of equilibrium between the reactions. Equilibrium between reactions generally is associated with sufficient time for the reactions to proceed to completion. In the case of the blast-furnace the time permitted is so small that final equilibrium cannot be attained.

The above reactions are equivalent to $\text{Fe}_2\text{O}_3 + 3\text{C} + 3\text{CO}_2 = 2\text{Fe} + 3\text{CO} + 3\text{CO}_2$, and the ultimate result is the reduction of two atoms of iron by three atoms of carbon.

The property of solubility in a fuel instead of being detrimental results therefore in a saving of fuel. It allows of heat-absorbing reactions taking place side by side with reactions which give out heat, which, however, is wasted if allowed to take place in the upper portions of the furnace. Activity of the carbon facilitates considerably the reduction of the ore by some such series of reactions as outlined above.

The crux of the whole position lies in the hearth. This is essentially the laboratory of the furnace. In this zone the temperature and other conditions are such that reactions take place in exceedingly short periods of time as compared with the other portions of the furnace. This is the zone in which modifications of the conditions have been most fruitful of results from the point of view of fuel economy, whilst theory as well as practice support the view that pronounced activity in the fuel arriving at this zone would have far-reaching results on the thermal efficiency of the furnace. From the practical standpoint, the results obtained with hot-blast, and later with dry blast, show that a small increase in the chemical and thermal activity of the hearth reactions plays a very much greater part in determining the final fuel economy of the furnace than would ever have been calculated from the old-time thermal balance-sheet.

From a theoretical standpoint the critical temperature theory opens up considerable possibilities in the employment of an active fuel, and whether the theory be true in all its applications or not, the conception is one which, so far as the hearth is concerned, does explain some of the more obscure phenomena in blast-furnace practice.

In all probability the increase of activity in the fuel will result in a contraction of the zone of combustion, with at the same time an increase of temperature. Further, not only will the temperature be increased, but at the same time the critical temperature will be reduced.

Johnson defines the critical temperature as the free running temperature of the slag, which is determined largely by the

composition of the slag. One of the most important factors in determining the free running temperature of the slag is the proportion of sulphur in the fuel. Johnson¹ states that sulphur removal can be effected by: (1) Increasing the lime in the slag, or (2) by increasing the hearth temperature. An increase in the lime content, however, results in a rapid increase in the free running temperature of the slag. The available heat therefore is reduced, and to supply this an increased expenditure of fuel is necessary.

On the other hand, Johnson points out that "an increase in blast temperature is much more effective in promoting desulphurisation than a considerable increase in limestone." This established fact of practice agrees with the results of the investigation of James Bell, which tended to show that with a slag of moderately basic character a considerable proportion of the sulphur is eliminated by volatilisation, an action which is prevented to a large extent by an excessively basic slag. A reactive fuel, by increasing the hearth temperature reduces the basicity required in the slag.

A further important consideration which has a bearing upon the critical temperature is the carburisation of the iron, a by no means negligible feature in the furnace operations.

Reactivity of the coke increases the rate of carburisation of the iron as is shown by the following experiments which is typical of a series conducted.

Mild steel turnings intimately mixed with equal weights of the fuels specified (graded in size between 12 and 14 mesh) were gradually raised to a temperature of 1100° C. and maintained at that temperature for thirteen hours. The carbon content of the steel was increased as shown in the following table:

Fuel Used.	Carbon in Original Steel. Per Cent.	Carbon in Steel after Treatment. Per Cent.
Foundry coke	0·08	0·45
Fuel prepared as described on p. 59	"	1·89
Wood charcoal	"	1·79
Precipitated carbon	"	1·15

The melting point of pure iron is about 1500° C., whereas the melting point of iron containing 1·9 per cent. carbon is about

¹ *Op. cit.*, p. 199 *et seq.*

1150° C. Therefore, if conditions in the furnace permit of the more easy absorption of carbon, such iron could be melted more readily, and a lower temperature would suffice.

There is finally a most important feature in connection with blast-furnaces to be considered. First, however, the function of the operation is to reduce and melt the iron, leaving as little iron in the slag consistent with economy and the resulting quality of the iron ; but maximum economy will only be obtained when the full power of the furnace is utilised. If, therefore, it be possible to obtain the results required by using not only the reducing power in the shaft, but also to permit reduction to take place in the hearth and still secure the desired quality, output, and iron residues in the slag, a further step to fuel economy will have been achieved.

Now, as already observed, in a charcoal furnace with low consumption, considerable reduction takes place in the hearth, and such reduction, owing to the conditions, must mainly be effected by solid carbon. As shown from a chemical standpoint, such reduction is effected with one-third the carbon required for reduction by carbon previously oxidised at the tuyeres ; hence, provided this can be done and the required temperature and heat balance still retained, so much to the good will have been obtained.

When the slag and metal is melted in the bosh it trickles down over the slag and stone, and gradually reaches the hearth, and it is known that as it does so, it does not at first exist in the state in which it leaves the furnace ; the slag still contains much oxide of iron, and the iron still has to dissolve further carbon. For the present only the slag containing ferrous oxide need be considered. Assuming that the ferrous oxide has in the main to be reduced before arrival at the hearth, it must, being in this liquid state, receive its carbon by actual contact. Let us therefore follow as well as we can the course of a drop of such slag on its way to the hearth.

Assume the furnace to be using ordinary refractory coke and operating normally. In such circumstances the furnace will have adjusted itself to the conditions and will be running with slag still containing some iron ; with a refractory coke the critical temperature compared with a charcoal furnace will be

high, and owing to that high temperature the coke will be in an active state.

As a drop of slag falls on the coke, the reaction $\text{FeO} + \text{C} = \text{Fe} + \text{CO}$ will take place at the point of contact and take place instantly, and this reaction is one accompanied by loss of heat. Since the specific heat of ferrous oxide is not actually known at high temperatures, it is not possible to ascertain the extent of this loss at high temperatures, but calculated from zero, the heat absorbed would be 36,528 calories. This loss of heat would have the effect of solidifying the drop of slag momentarily and checking its fall until it had collected sufficient heat again to permit it to continue its course. In this way the temperature of the furnace, by rendering the carbon active, has checked the passage of the slag and permitted it to collect further heat to allow the reaction to be repeated, until by the time it enters the bath, little further reaction remains to be effected there by contact with the coke submerged in the well.

If the slag contain little ferrous oxide, this delayed action will be less, and it will run more freely to the hearth; thus, if reduction be more complete in the shaft, little delay will occur.

Now consider the same drop of slag in a similar furnace running cold. Under such conditions the slag will have adjusted itself and will contain more ferrous oxide. Hence it will be more fluid, and the temperature being lower, the reaction between the carbon and ferrous oxide will not be active and the delay will be less marked, with the result that in this case the slag arrives at the bath in an unreduced condition.

Now consider a similar drop of slag in a furnace using charcoal or a very reactive coke. As it will be running to take as much surplus heat from the hearth as possible, the slag may contain at the outset far more ferrous oxide than in a coke furnace, and the critical temperature will be lower, but in this case the fuel is far more reactive at this temperature than the hotter coke furnace, and the reaction ferrous oxide + carbon is far more intense. This condition retains and delays the slag, until the final traces of iron are reduced prior to its arrival at the bath. The above theory accounts to some extent for the increased carbon dioxide in the hearth of a charcoal furnace.

Assuming the correctness of the above views, it means that

from the hearth considerable quantities of carbon monoxide will be rising, and as the blast enters it will combine with either carbon or carbon monoxide; if carbon monoxide, it will produce carbon dioxide, which will react with carbon to form carbon monoxide. If 25 per cent. of the oxygen be removed in this region, quite appreciable amounts of carbon dioxide would appear in the gas analysis. A further point bearing upon this is that, assuming the deductions to be correct, the slag running in a charcoal furnace to the bath with a larger ferrous oxide content would have a lower melting point, which all bears upon the deduction that a lower critical temperature is required for such a furnace than in a coke furnace.

EFFECT OF AN ACTIVE COKE ON THE OUTPUT OF THE FURNACE.

The output of a furnace is dependent on the rapidity with which the fuel is consumed. In the past this has been measured per square foot of hearth area. Johnson,¹ however, points out that this basis was not a correct one. Combustion proceeds not in a plane, but in a zone embracing probably the whole of the bosh, and a more correct view would be the coke consumption per cubic foot of bosh space (see above). Owing to the velocity with which the blast passes through this region, the time available for the oxygen in the air to be converted into carbon monoxide would be less than one-third second, a time so small that combustion would only proceed in the outer surface of the coke. The air would not permeate into the interior of a coke lump.

It has been shown by Sir George Beilby² that a coke prepared in accordance with the procedure outlined on p. 59 is characterised by an extremely large surface area per unit of mass. In view of this, combustion could proceed with greater rapidity than is the case with normal blast-furnace coke. In other words, it would be possible with increased blast to burn an increased quantity of fuel in the hearth. On the other hand, owing to the reactivity of the fuel and the larger proportion used in the furnace for direct reduction for the same blast,

¹ *Op. cit.*, pp. 302 *et seq.*

² *Journal of the Society of Chemical Industry*, 1922, vol. xli. pp. 341-347T.

a larger consumption of fuel would be obtained with a more rapid lowering of the carbon, and consequently an increased output.

Assuming that an ordinary coke furnace producing 20 cwts. of iron with 20 cwts. of coke, all of which was consumed at the tuyeres in accordance with Gruner's ideal, and further assume that with a reactive coke a ton of coke was used per x cwts. of iron, of which 10 cwts. only was consumed at the tuyeres, then the output of such a furnace would be doubled, since its output depends upon the quantity of fuel the blast could consume.

This increase would reduce the heat losses, e.g. radiation, &c., which are dependent upon the time factor.

SUMMARY OF FUEL-SAVING FACTORS INVOLVED IN USE OF ACTIVE COKE.

It is now possible to summarise in a general way the various fuel economies that would be effected by the use of an active coke.

Taking the heat-absorbed side of the thermal balance sheet, the following changes could be expected :

1. Less limestone would be required—hence less heat would be absorbed by its decomposition.
2. Less slag would be made.
3. Owing to the reactivity of the coke, the top temperatures would be lowered, hence the loss in sensible heat would be reduced.
4. Owing to the smaller blast required per unit of iron with an active coke, the volume of gases leaving the stack would be lower than is normally the case, still further reducing the loss in sensible heat.

On the heat-produced side of the thermal balance-sheet, the proportion of carbon dioxide in the exit gases would be considerably increased.

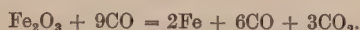
Lastly, from the point of view of the chemical side, the carbon requirements for the reduction of the ore would probably be much lower than is normally the case—owing to the increased amount of direct reduction that would take place.

The sum total of these effects is very difficult to estimate quantitatively, but an attempt can be made in a very imperfect

and tentative kind of way to get some idea of their numerical value in a furnace operating with reactive coke under ideal conditions.

THE LIMITS OF FUEL ECONOMY IN A BLAST-FURNACE FROM A CHEMICAL STANDPOINT.

The carbon requirements in a blast-furnace, working in accordance with Bell's hypothesis, can be calculated from the equation :



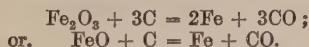
This equation requires the use of 19·6 cwts. approximately of coke per cwt. of pig.

On the assumption that reduction was effected entirely by carbon monoxide, and that the resulting proportions of carbon monoxide and carbon dioxide in the exit gases were equal, we would get the equation :



This equation requires the use of 12·58 cwts. approximately of carbon per ton of pig.

Instances, however, are known of fuel consumption below this figure, and these can only be accounted for on the assumption that a proportion, at any rate, of the ore is reduced directly by carbon in the bosh, according to one or other of the equations :



It might therefore be of interest to determine the theoretical possibilities involved in the reduction of pure ore, on the assumption that a proportion of the ore is reduced by CO, and that a proportion is reduced by solid carbon.

It has already been shown that by direct reduction two atoms of iron can be reduced by two atoms of carbon—a consumption equivalent to 4·28 units of carbon per 20 units of pig iron.

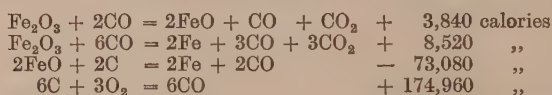
Assuming that carbon dioxide and carbon monoxide leave the furnace in equal proportions by volume, then :

- (1) If 20 per cent. of the ore is reduced directly by carbon, the fuel consumption per 20 cwts. of pig iron will be 11·13 cwts.

- (2) If 25 per cent. of the ore is reduced directly, the fuel consumption will be 10·7 cwts. per ton of iron.
- (3) If $33\frac{1}{3}$ per cent. of the ore is reduced directly, the carbon consumption will be 10 cwts. per ton of iron.
- (4) If 50 per cent. of the ore is reduced directly by carbon, the fuel consumption becomes 8·57 cwts. per ton of iron.

The calculated consumption in the last case is lower than anything yet recorded, but no assumption has been made which is contrary to results already reported. Moreover, a carbon consumption of only 10·98 cwts. per ton of pig iron has already been reported by Bell,¹ whilst it can readily be shown that the thermal requirements can be satisfied with a pure ore with a consumption of 8·6 cwts. of carbon per ton of iron.

Case (4) can be represented by the following series of equations :



(N.B.—These reactions are assumed to begin and end at normal temperatures.)

There is a surplus of heat from the above reactions of 114,240 calories. Of this, the heat required for fusing the iron and bringing it to tapping temperature is 72,000 calories. The surplus for other purposes is 42,200 calories. As the ore is pure and very little slag is produced, this is theoretically sufficient to cover the radiation and other losses. Further, the gases leaving the furnace, containing as they do equal volumes of carbon monoxide and carbon dioxide, would have sufficient calorific value to heat the blast, and thus allow of further reductions in the carbon consumption. This, of course, is purely theoretical speculation, but looking back on results previously recorded, it does not appear as far-fetched as it appears at first sight.

In the case of an ore containing a low iron content and giving a high slag yield, a considerable amount of heat is required for purposes which play no part in the chemical reactions. A study of the requirements in this direction shows that the excess fuel for this purpose considerably exceeds the fuel required, say, for

¹ "Principles of the Manufacture of Iron and Steel," p. 304.

merely fusing the slag, and raises the question whether the time is not ripe to consider the possibilities of ore treatment prior to use in the furnace for the purpose of reducing the quantity of silicious gangue now associated with it. The matter has already been touched upon by Mr. T. C. Hutchinson and Mr. H. E. Wright in papers to the Institute. If this could be done economically there are possibilities of reducing the fuel consumption, if not to the theoretical limit, yet to a point considerably below that of existing practice.

From whatever standpoint the matter is investigated, it appears probable that a highly active fuel of the type described in this paper opens up far-reaching possibilities in blast-furnace practice. Difficulties may, and probably will, arise in its practical applications, existing furnace designs may have to be altered to meet with the new conditions to the best advantage, factors as yet unforeseen may upset the calculations advanced in these notes; but, taking everything into consideration, the authors believe that the primary quality of the blast-furnace fuel of the future will be reactivity of such a character and of such a degree as will make it necessary to recast in many respects the previous views of experts with reference to the limits of fuel economy in the smelting of iron.

THE "REACTIVITY" OF COKE.

ADDENDUM BY R. V. WHEELER.

The subject of the "reactivity" of coke—that is to say, its power of reacting with oxygen or with carbon dioxide—is one that demands intimate study, with a view to determine the factors upon which the reactivity depends. Apart from this intimate study, however, there is a need for means of obtaining an accurate measure of the reactivity of different samples. It is with this branch of the subject that this note deals. The more complicated research now being carried out in the Fuel Department of Sheffield University, on the factors that determine the reactivity of coke, is still in its early stages, and any discussion of the results so far obtained would be premature.

The method adopted to determine the relative rates of reaction between different solid carbonaceous fuels and (a) oxygen and

(b) carbon dioxide is essentially that used by Rhead and Wheeler in their work on the combustion of carbon¹; the apparatus being a modification of that described by Bone and Wheeler.² The apparatus (see Fig. 1) consists essentially of a closed system in which the gas (oxygen or carbon dioxide) is circulated through a column of the coke, which is heated at a known constant temperature in an electric furnace.

The glass globe A serves as a reservoir for the gases. It is connected by a ground joint B with a porcelain tube in which the fuel is packed. A similar ground joint B1 makes connection with a calcium chloride drying tube C, and the head of an automatically acting sprengel mercury pump D, by means of which circulation under atmospheric pressure can be effected. This pump draws the gases from the globe through the tube containing the fuel (the "reaction-tube"), and delivers them under mercury into the wide manometric tube E, whence they return, along the horizontal tube F, to the globe.

A mercury manometer G is fixed near the globe and serves for observing the pressure inside the apparatus, and thus following the course of the reaction.

The reaction tube is by-passed by the tube H, a glass spiral being inserted to avoid rigidity, so that when taps L, L', are closed, and M, M', open, the gases can be drawn round the apparatus without passing through the fuel. In some experiments it is necessary to obtain samples of the gases in the apparatus at different stages in the reaction. For this purpose the by-passed sampling tubes N can be inserted in the circuit at any convenient point (preferably near the globe, as indicated by the dotted lines in the diagram, a portion of the horizontal tube F being cut away and the sampling arrangement fused in its place). It will be seen that the arrangement of taps on these tubes allows of a sample being shut off without altering the pressure of the gases in the main body of the apparatus, and therefore without interfering with the course of the reaction. Similarly, a by-passed absorption tube R can be introduced elsewhere in the circuit for use when, as during oxidation experiments, it is desired to remove absorbable products of reaction as soon as they are formed.

¹ *Transactions of the Chemical Society*, 1912, vol. ci. pp. 831, 846.

² *Philosophical Transactions of the Royal Society*, 1906, vol. cexvi., A, p. 1.

The reaction tube is 26 centimetres long and of 1.2 centimetres internal diameter. The fuel, weighing about 2 grammes

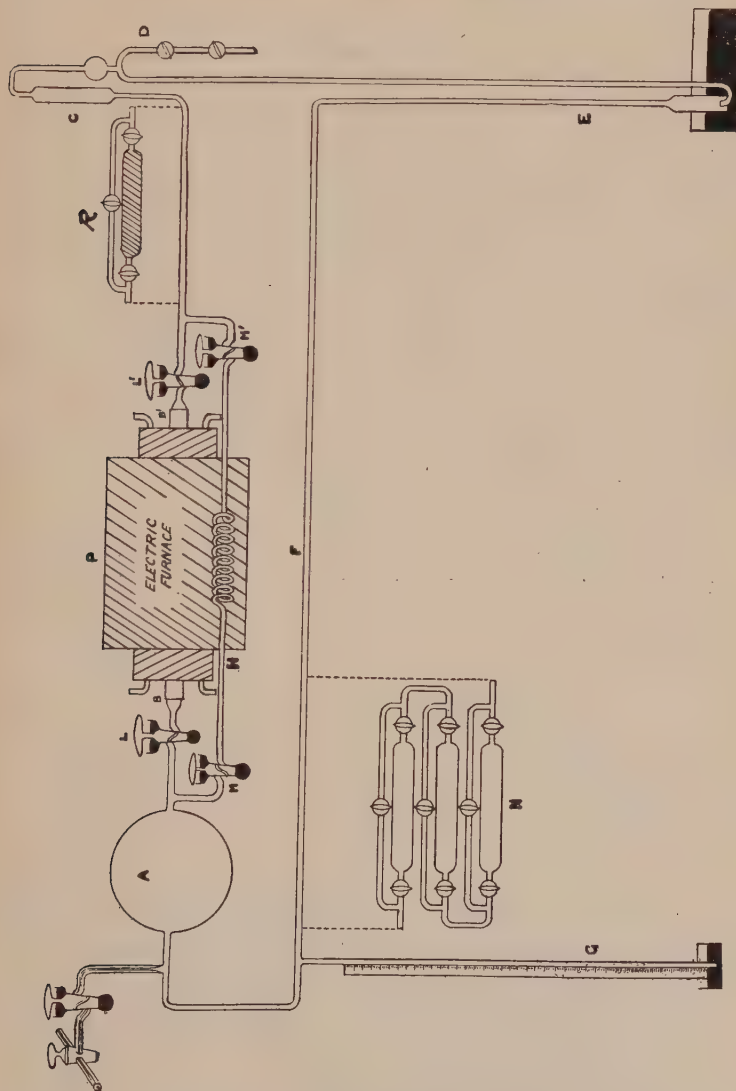


FIG. 1.

and sieved through a 10 and on a 30 mesh sieve so as to be of uniform size, is contained within a sleeve of quartz which occupies the middle 9 centimetres of the tube only and is kept in

position by plugs of a small-bore quartz tubing which just slides into the porcelain tube.

Preliminary experiments with wood charcoal showed that the temperatures at which the reactions proceeded at a convenient rate were (a) for oxidation 400° C., and (b) for reduction of carbon dioxide 900° C. Oxidation at 400° C. results in the formation mainly of carbon dioxide, a trace only of carbon monoxide being produced; the progress of this reaction, therefore, can be followed in the apparatus by a fall in pressure of the gas if the carbon dioxide is removed as soon as it is formed. The reduction of carbon dioxide by carbon is accompanied by an increase in volume; the progress of this reaction can therefore be followed by an increase in the pressure of the gases.

Both reactions can be regarded as unimolecular, and van't Hoff's expression, $1/t \cdot \log \frac{C_o}{C_t} = K$, can be employed for determining the relative rates.

Some of the results obtained are as follows:

Oxidation at 400° C.

Sample.	K (t = 1 Minute).
A. Wood charcoal	0.000452
B. " Activated " carbon	0.001398
C. Foundry coke	0.000084
D. Gasworks coke	0.000672
E. Sutcliffe, Speakman & Co.'s fuel	0.000414

Reduction of Carbon Dioxide at 900° C.

Sample.	K (t = 1 Minute).
A. Wood charcoal	0.000432
B. " Activated " carbon	0.000705
C. Foundry coke	0.000049
D. Gasworks coke	0.000158
E. Sutcliffe, Speakman & Co.'s fuel	0.000293

Other series of determinations are in progress with different varieties of coke at different temperatures of experiment. It is probable that a temperature of 450° C. will be found most suitable for routine determinations of the rate of oxidation, and 950° C. for the rate of reaction with carbon dioxide. A works method of determining the rates will be developed from the laboratory method, the apparatus for the latter, though simple enough to use, being rather complicated to instal.

DISCUSSION

Mr. DAVID BROWNLIE (London) said two problems were involved in the subject of the paper: fuel economy and agriculture. Without wishing to appear melodramatic, he nevertheless thought if those two problems were not solved Great Britain would go under. The iron and steel industry was associated very closely with the question of fuel economy and problems connected with coal, and alone consumed about thirty million tons of coal per annum. The authors' work was thus remarkably important in that connection. He thought that it was not altogether realised what it was the authors had discovered. From a national point of view it was necessary to abandon the wasteful practice of burning raw coal. About 260,000,000 tons of coal per annum were at present being raised in Great Britain, of which about 190,000,000 tons were burnt at home. Of that quantity only some forty million tons were consumed in the form of carbonised fuel, and the valuable by-products—ammonia, motor spirit, liquid fuel, and gas—in about 150,000,000 tons of coal per annum were wasted. The iron and steel industry played a very large part indeed in the squandering of coal, and two typical examples were waste of blast-furnace gas and the waste of coke-oven gas in the making of coke. The authors had discovered that it was not necessary to have a certain volatile content in order to make a fuel combustible. Ordinary semi-bituminous coal, containing 30 to 35 per cent. of volatile matter, burned easily but it also smoked badly. As that coal was slowly carbonised and the amount of volatile matter reduced, the amount of smoke became less, but the fuel ignited with less ease. When the stage was reached at which the amount of volatile matter was reduced to 13 or 14 per cent. the fuel ceased to smoke at all, but, at the same time, it still burned fairly easily. The main object of low temperature carbonisation, of which there were about forty-five different processes in existence, was to produce a smokeless fuel which ignited without difficulty. The authors had discovered a very remarkable fact—namely, that it was not necessary to have 10 or 12 per cent. of volatile matter present to make such fuel burn easily. By producing the fuel in a peculiar granular and porous condition, something like charcoal, they had produced a smokeless fuel that ignited without difficulty, although it only contained as low as 1 per cent. volatile matter. It had also a very high reactivity, and it was that very high reactivity which led the authors, and rightly so, to believe that they would get with their fuel in the blast-furnace the same high quality of pig iron as that originally obtained with the old charcoal process. In his opinion,

the iron and steel industry would be well advised to try out the process on a large scale as soon as possible.

Looking at the matter from the national point of view, if the 20,000,000 tons of coke which were used in the country in the iron and steel industry could be used in the form of that particular fuel, there would be something like 100,000 tons of sulphate of ammonia alone available over and above what there was at present from the coke-oven industry, together with about 40,000,000 gallons of benzol, and about 4000 barrels of oil. They could not go on continuing to squander the valuable volatile matter in raw coal and, in his opinion, the authors' process was one of the most important in connection with the problem that had so far been brought forward. It should be pointed out also that one valuable feature would be the large amount of fixed nitrogen in the form of sulphate of ammonia that would be available for the cultivation of our soil.

In conclusion, he would like to ask the authors a question. Taking a very moderate output—1000 tons of pig iron per week—on present average practice 1250 tons of coke would be required, which involved the carbonisation of 1800 tons of coal per week. He presumed the authors' system involved the use of something like 12 to 14 cwt. of their fuel to a ton of pig iron, and at any rate would presumably be less than coke. What would be the cost of an installation for the production of this new fuel for a blast-furnace plant of moderate size, producing 1000 tons of pig iron per week? It might be thought that the installation would be very large and costly, especially the briquetting plant, and would be subject to considerable wear and tear. He hoped the authors would deal with that matter in their reply, as the success or otherwise of the process would obviously turn largely on those points.

Mr. W. J. FOSTER (Kenilworth) said he did not propose to deal with the paper from the point of view of the manufacture of coke so much as in regard to the principles involved in blast-furnace science and practice. The report of the British Association Committee referred to stated that it was advisable not to economise coke in a blast-furnace beyond what was required to supply gas to drive the auxiliary plant and external heating generally from the blast-furnace itself. He was sorry to have to disagree with that statement. It was obvious to all blast-furnace managers that coke had cost, during the past thirty years, nearly four times as much as slack, and it certainly had fewer calories than slack. The result was that a gas-producer for producing gas must of necessity be at least four times as efficient if it came to purchasing calories.

The authors referred to the velocity of gases through a blast-furnace as calculated by Johnson, who was quoted as saying that the gases passed through a blast-furnace and into the atmosphere or downtake in two seconds. That statement was quite correct under certain

conditions, but it would involve a tremendous explosion. The blast could not possibly pass through the furnace in that time without such an explosion (or other abnormal conditions), because it might have to travel 80 feet through the material in a zigzag fashion, which meant that the distance might be multiplied from two to ten times, according to circumstances.

Sir Lowthian Bell was said to contend that 25 per cent. of ferrous oxide passed through the materials into the hearth, while Johnson assumed that it would be 10 per cent. Both statements were correct in certain circumstances. It might be 5 per cent. or 50 per cent. ; there was nothing definite in the statement at all.

On p. 36 Mr. Johnson was referred to in regard to the quantity of blast which gasified the carbon at the tuyeres being taken as the measure of fuel economy. Mr. Johnson contended that the greater the amount of blast that entered the tuyeres and the more carbon oxides which were made from the carbon, the greater the efficiency and the smaller the quantity of coke which was necessarily required. He (Mr. Foster) had proved that statement to be far from true ; the reverse, in fact, was the case. In blast-furnace practice to-day, as in the past, the management should aim at gasifying as little as possible at the tuyeres in proportion to the amount of iron made. It did not follow that if the quantity of blast per minute were increased more carbon would be gasified per ton of iron made. It might be less. Everything depended upon the circumstances. The maximum reduction by solid carbon demanded a minimum supply of atmospheric air with greater efficiency.

He would like to draw particular attention to the statement made by the authors on p. 44 of the paper regarding his own attempt to ascertain the efficiency of blast-furnaces in a different manner from that in previous use. He did not say it was the best, because it had to be proved ; but he was there to defend it. In that particular case the question was whether the gases in charcoal had any effect on the efficiency of charcoal in a furnace in protecting the oxidation or, as the authors called it, the solubility ; that is to say, the action of CO_2 on solid carbon. He contended now, as then, that the gases eliminated from charcoal, which amounted in ordinary commercial charcoal to 171 times its own volume, constituted a great saving and protected the action of solubility. Those gases usually included ammonia, which contained hydrogen and nitrogen. Nitrogen, being inert, did not affect the situation so much. But the hydrogen, leaving the charcoal at a temperature of somewhere about $400^\circ \text{C}.$, had a reducing action on oxide of iron. The oxides of iron introduced into the charcoal furnace were usually very rich and easily reduced at a temperature of about $200^\circ \text{C}.$ Nascent hydrogen eliminated from the charcoal often took up oxygen immediately and went off as steam or water. Further, it had to be clearly understood that charcoal produced very little ash, and that that was in the form of alkali, particularly potassium.

Potassium salts melted at very low temperatures, and long before the potassium reached the bosh of the furnace they melted, and so protected the fibre of the carbon to a certain extent by saturation, most of it forming cyanides. The ultimate result was that the potassium left the charcoal, and any decrepitated or fine charcoal coming from the action of abrasion or crushing was oxidised on approaching the bosh and hearth at ordinary working temperatures; the gases at their average velocity would remove that charcoal and so prevent it from accumulating on the bosh and hearth as the coke did. That reduced any oxide of iron which approached the bosh and the hearth for further reduction, or presented itself for oxidation at the tuyeres when in excess. On the other hand, coke contained alumina and silica, either of which might be in excess and both of which were infusible, or practically so until they reached the hearth or the bosh, with the result that there was probably 12 per cent. of that material which accumulated in masses of soft or hard coke dust with the semi-fused ash which rested on the bosh and hearth. After a certain period the furnace assumed the form of a channel, and the area of the bosh and hearth were reduced as well as the efficiency of the furnace. That was not the case with charcoal. There was no comparison in that respect between charcoal and coke.

Mr. A. K. REESE (Penarth) thought the authors need not have laboured to prove to the Institute that reactivity or a high rate of combustibility in fuel was of advantage in blast-furnaces. He knew of no blast-furnace-man of to-day who would question for one moment the statement that a high rate of combustibility was desirable. The authors' object may have been to lead up to the very remarkable and radical theory which they announced in the latter part of their paper. It was impossible at the meeting to discuss in detail the arguments presented by the authors. He questioned whether any end would be served by doing so, because it would really be an academic discussion of a theory which was opposed to all preconceived theories, and was not based, he thought, on any ascertained facts.

A comparison was made between the charcoal furnace and the coke furnace, or rather between charcoal in a charcoal furnace and coke in a coke furnace. He was not quite sure whether the authors meant to imply that the conclusions they had drawn from their reading of the action of charcoal in a charcoal furnace would apply to the action of coke or charcoal in a coke furnace; that is to say, a modern coke furnace. If that was the authors' intention he thought their conclusions were not justified. The two things were very different in many respects. The object of the paper apparently was to bring out the idea that the solution of carbon in a furnace was a beneficial reaction, and that direct reduction was also a beneficial reaction. No one would contend that those reactions did not occur in a well-operated blast-furnace. They all knew that under blast-furnace

conditions those reactions must occur to some extent, owing to the unavoidable contact between the incandescent fuel and the ores at the temperatures which existed in the furnace, in the passage of the carbon dioxide over the heated fuel. The question was whether those reactions should be stimulated for the purpose of obtaining greater economy, or reduced. All existing evidence went to show that a reduction of those reactions would increase the fuel consumption, and all past attempts had been in the direction of reducing those reactions. The authors claimed that the effort should be in the opposite direction, and that those reactions should be increased if possible.

He had no wish either to damp the spirit of the authors or to discourage them from obtaining a practical trial of their fuel. That, of course, would be the best thing to do, and he hoped they would succeed in inducing ironmasters to make a practical demonstration of the fuel. If the claims that were made in behalf of the efficiency of the fuel could be substantiated, theories as to how that efficiency was obtained could be profitably discussed later on.

He would like to ask why the authors asserted that a soft friable fuel, or a fuel which was easily reacted upon by carbonic acid gas, would not result in any loss of fuel if the reaction took place in the upper part of the furnace. If the reaction took place there, as no doubt it did, that carbon was certainly lost to any further use in the furnace operations. It was the reaction in the upper part of the furnace, in what was commonly called the reducing zone, that the solution of carbon was particularly objected to as resulting from a soft and easily acted upon fuel.

If direct reduction were an economical reaction, it certainly would and should be the object of every blast-furnace operator to bring his ore and coke into intimate contact as early as possible in its passage through the furnace, because it was only by direct contact that reduction of solid carbon could possibly take place. As a matter of fact, the almost universal method of charging a blast-furnace was to charge it with the coke in layers of varying thickness, and the ore in layers. That tended to reduce the direct contact of the coke and ore in the upper or reducing regions of the furnace, and had an opposite effect to that which the authors stated to be desirable. He had known a furnace to be charged by mixing the ore and coke and limestone intimately together in the skip, and the furnace charged with the mixture. In that case there was the highest degree of contact between the ore and the coke. That furnace did not do very well in fuel consumption, and the charging system was changed to one in which the coke was put in in layers of about 2 feet thick or more and the ore was charged separately in layers. That led to an immediate and marked reduction in fuel consumption and brought about a better working of the furnace, which seemed to demonstrate that intimate contact was not desirable in the upper part of the furnace, where it was desirable to reduce reduction by solid carbon. Those two features constituted

some evidence which was contrary to the claims of the authors, though he would not say it necessarily disproved them.

The authors rather easily disposed of the solution theory by claiming that all troubles due to inferior qualities of coke were due to irregular physical action in the furnace. There was no doubt that that had a very material effect upon the working of a furnace with friable or soft fuel; but it was somewhat too easy a method of disposing of the old and established theories of the solubility of soft fuel, and the authors' arguments in sustaining their claim seemed to him to be rather meagre. He hoped they would be able to substantiate their claims, because, if they did so, the advantage to the iron and steel industry would be tremendous. But he thought they ought not to talk about their theory very much more until they had carried out a practical demonstration which proved it to be correct.

MR. ALFRED HUTCHINSON, Member of Council, said there was some truth in Mr. Reese's contention that the paper was somewhat academic in character, and he had been wondering whether some practical outcome might not result along the lines which he proposed to state. On p. 58 of the paper the authors suggested the kind of practice they wanted: "Preparation of the coal prior to combustion: (1) Efficient cleaning; (2) preliminary treatment or blending of coals or coke to insure a minimum of swelling in the retort; (3) fine grinding of the coal; and (4) briquetting of finely divided coal mixture." For some time he (Mr. Hutchinson) and others had tried to get a thoroughly clean coking coal by means of the froth flotation method and, so far as the cleanliness of the coal went, it proved quite satisfactory. They had, however, been up against the difficulty of efficiently drying the coal, which was so thoroughly wetted in the mineral separation process. They had worked for some time along the lines of hydraulically pressing the purified coal to produce a kind of briquette. From the point of view of the briquette industry, that had been very successful; but they were not satisfied whether it would pay to install a plant for coking the coal by means of which it could all be briquetted and then transferred to the coke-oven. But, if the saving in coke consumption in the blast-furnace was anything like that suggested by the authors, it might pay them to install a plant to carry on commercially the work which they had already succeeded in doing experimentally.

MR. FRED CLEMENTS (Park Gate, Rotherham) said he had some information he would like to communicate. The previous day he had visited an experimental plant of considerable capacity in which iron had been produced from Frodingham ore with an expenditure of only 900 lbs. of bituminous coal per ton of iron made. That was not fiction, but a fact for which he could vouch. He was not at liberty at the moment to explain the process in detail, but it would be noticed that the figure corresponded fairly closely with the theoretical figure

put forward by the authors in their paper, namely, $8\frac{1}{2}$ cwts. It was effected partly by direct reduction and partly by indirect reduction, and the proportion of $\text{CO} : \text{CO}_2$ was far lower than anything previously obtained. That being so, it seemed to him there was considerable support for the hopes expressed by the authors. It was, he felt, somewhat difficult, if not dangerous, to try to deduce what would happen in a coke-fed furnace from what happened in one fed with charcoal, and he agreed entirely with Mr. Reese's suggestion that the only way in which the authors' proposition could be tested was in actual practice. There seemed to be sufficient support for the theory advanced in what had already been achieved to justify a reasonable expenditure in putting it into practice. Theories could be discussed indefinitely, but "faith without works" was dead.

There was an essential difference between the charcoal furnace and the coke furnace in the degree of fusibility of the ash, and that was more favourable in the case of the former. It could be easily realised that in any furnace there was a level of temperature, depending on the fusibility of the materials, which had to be reached, otherwise below that temperature an indefinite amount of heat could be developed in the furnace without any effective work being done. Immediately the critical level was passed production proceeded, within limits, with increasing rapidity. In a charcoal furnace with its smaller quantity and more easily fused ash the critical intensity of temperature was more readily attained than it was in the coke furnace. In his opinion, that accounted largely for the difference in the experience with the two fuels.

Mr. C. H. RIDSDALE (Middlesbrough) said he had devoted a number of hours to the paper, and felt after he had finished as though he had had a very heavy meal which he could not digest. At the same time, there was undoubtedly very much to learn from it, and thanks were due to the authors for their courage in bringing forward a suggestion of the sort and challenging the theory and detail of blast-furnace practice. He thought the authors had departed somewhat from the remarks made on former occasions by Mr. Evans. Mr. Evans had spoken of making a ton of Cleveland iron with 12 cwts. of coke. The suggestion now was that the problem was allied with the question of cleaning the material, whereas the cleaning of the material was quite a different problem, although it was one that almost every blast-furnace manager would like to solve and could not. It was important to differentiate between the question of improved results due to using coke of high combustibility, or "reactivity," and those obtained by the cleaning of the materials. It would be interesting to have records of the impurities per ton of pig iron in the burden of those furnaces that had produced iron with less than the usual and theoretically necessary amount of coke, or with charcoal. Such records would throw light on the whole question, because there was very little data

on the subject. The problem, as he looked upon it, was to get a low consumption by means of Mr. Evans's coke with such iron-making materials as were actually available. One knew what sort of coke and what sort of ore one would like, but in the outcome it was necessary to take what was given.

In reference to the desirability of all reduction being effected by solid carbon, obviously the more reduction that could be effected by that means in contradistinction to carbon that was first burned, the less was the weight of inert gases that had to be introduced, as there was then no necessity to introduce nitrogen to the weight of three and three-quarter times that of the oxygen. In that way some advantage might be obtainable. On the other hand, data were available: he had quoted some himself at the Institute five or six years before¹ as to the experimental working of a furnace, in order to discover how much Gellivara ore could be used as a maximum. All the reduction in that case was done practically at the tuyeres, or just close above them, and instead of there being a much lower coke consumption, the consumption was much higher. No matter what theory was advanced, when the carbon had been burned to carbon monoxide it passed up through the furnace and reduced the ferric oxide present, in the upper 20 or 25 feet of the furnace, and therefore there was bound to be carbonic acid formed. He quite agreed with the point made by the authors about the extreme sensitiveness of the hearth, which, of course, would account to some extent for economies which might be made by using a more rapidly combustible coke. Still it seemed the real crux of the matter was that the authors' suggestions had not been tried out, and he would ask them what hindered their making a practical trial?

CORRESPONDENCE.

Mr. E. ADAMSON (Sheffield) wrote that he had been much interested in the paper, particularly as he was convinced that up to the present there had been a tendency in the production of foundry irons to go for rapid working and increasing outputs, even at the expense of quality. Theories as to the various reactions taking place in different parts of the blast-furnace were, to a general extent, speculative, but it would probably not be denied that the fewer compound heat reactions (that was, endothermic and exothermic) there were, the greater would be the fuel economy. Modern practice was tending towards greater intensive heat and combustion in the melting zone immediately above the tuyere area, thus giving cooler gases on leaving the furnace.

It was a long accepted fact that charcoal furnaces burned less fuel per ton of pig iron smelted than the coke furnace, one of the reasons

¹ *Journal of the Iron and Steel Institute*, 1917, No. II. p. 50.

no doubt being that charcoal was lighter than coke, and thus less weight of fuel was required between the charges. With charcoal there was, further, a greater likelihood of ore reduction by solid fuel, which would decrease the necessity of the compound reactions referred to above. The reason why hard, strong, ringing coke was preferred by blast-furnace managers was because they found less fuel was required per ton of iron smelted, for not only did it carry the furnace burden better, but it was more effective in its reduction of the oxides. Again, charcoal would not give such a "keen" oxidising heat as coke, and therefore the nearer the authors got to the charcoal ideal, not only would there be greater fuel economy, but a superior quality of iron would be produced, and as Mr. Clements pointed out, it was easier to keep an even temperature in the charcoal furnace.

Dryness of fuel was, as Mr. Hutchinson pointed out, also a great feature, and if the authors were not able to arrange for a trial in a large modern furnace, it may be possible to carry one out in a small charcoal furnace.

Mr. G. W. HEWSON (Jarrow-on-Tyne) wrote that it was conceivable that the use of such fuel as the authors not only proposed, but were prepared to produce, might become as great a boon to ironmakers as the introduction of hot-blast, in the saving of fuel and more efficient working of the blast-furnace. Whether the quality of the iron produced by the new fuel would revert in some degree to the physical quality possessed by cold-blast and charcoal iron, of course remained to be proved in a practical way. At present, however, the chief point under discussion was the question of economy of fuel, accompanied by no diminution in output or deterioration of quality in the iron. As he (Mr. Hewson) had had the privilege of examining some of the fuel advocated, his observations may be of some value and interest.

A quantity of fuel made from non-coking coal (using that term in the sense generally understood at the present time) was put through the "hardness test" described in the *Journal of the Iron and Steel Institute*, 1918, No. I., and proved from that standpoint to be equal to the average coke made from Durham coal, which was itself considered the best coking coal obtainable. In that respect, therefore, it was safe to assume that that fuel would not suffer any greater loss by abrasion than did Durham coke.

The question of the reactivity of the coke resolved itself into two phases:

- (a) The rate of combustion of the carbon in air, now denominated the combustibility of the coke.
- (b) The rate of solubility of carbon in carbonic acid to form carbonic oxide, and denominated the "reactivity" of the coke.

Both those phases were influenced by the time of contact and the temperature at which the reaction took place.

As Messrs. Sutcliffe and Evans pointed out, the question of equilibrium hardly applied, as the period during which the reacting gases were in contact with solid coke at any particular point in the furnace was very small, and recognition of that fact made one hesitate to take figures obtained in laboratory experiments, as to solubility or reactivity, as a guide to what might occur in a blast-furnace. The claim of the authors that a fuel which gave a higher initial temperature at the tuyeres was more economical in a furnace was generally conceded, and probably their explanation as to its leaving less oxygen residue in the gases to consume coke higher up the furnace was correct. It was also a recognised fact that hotter working in the tuyere zone meant colder exit gases, and hence the amount of solubility of coke in carbonic acid gas high up in the furnace was reduced; or, in other words, the coke was not so easily attacked by CO_2 in the upper region of the furnace, and as it descended the furnace under those conditions the concentration of CO_2 diminished and the temperature increased, hence the danger of solution loss was diminished, and a greater proportion of the original coke charged reached the tuyeres. Other points which needed further elucidation, and which the paper suggested, were the relative rate of reactivity of CO in the gas with oxide of iron, more particularly when the latter was reduced in quantity to a low figure.

Further, it was possible that the rate of reactivity of CO_2 and C in the neighbourhood of the tuyeres might be so great as to leave no carbon to effect final reduction of the oxide of iron. Perhaps those questions could not be satisfactorily solved until a practical and prolonged trial had been made with that fuel.

Mr. T. D. MORGAN (Cardiff) wrote that in discussing the merits of coke and charcoal in blast-furnace practice E. Belani pointed out that, in order to estimate the working value of a fuel in the blast-furnace, the entire contents of the zone of combustion had to be taken into consideration, as well as the rapidity of the combustion, as the greater the quantity of heat which the unit of fuel produced when burnt in the unit of time, the less would be the loss of heat in the same period, and the greater would be the quantity of heat which would be available for absorption by the charge. Consequently, with different fuels the smallest quantity required for a given purpose would fall to that which in the units of time developed the maximum quantity of heat.

The heat developed by the unit weight of fuel in the unit of time depended (1) on the size of the surface exposed to the action of the blast, and (2) on its relative combustibility. Further, the more combustible the fuel, the more it would burn away in a given time, and the greater would be the surface exposed to the blast during the period. Consequently combustibility and exposed surface were relatively identical. The relatively lower quantity of heat developed by the coke in the unit of time, resulting in the consumption of a larger quantity

of fuel, was one of the chief causes of the poorer quality of the pig iron produced when coke was used as a fuel.

If it were possible to obtain coke in as voluminous a condition as charcoal, the results would probably be similar. The main point aimed at in the paper appeared to be the production of coke having similar physical structure and properties to charcoal. Assuming that that would become possible, the difference in the chemical composition of the two kinds of fuel (especially the available carbon, ash, sulphur) would have to be considered. As the carbon was the element that furnished the heat, the more the fuel contained the greater would be its heat value. Taking as an example the following analysis of coke and charcoal :

	Coke per Cent.		Charcoal per Cent.
Fixed carbon . . .	85.00	Fixed carbon . . .	90.00
Ash	12.00	Ash	1.50
Sulphur	1.00	Sulphur	0.05

the available carbon (that part of the carbon that was left after deducting from the fixed carbon of the coke the amount necessary to melt the slag formed by the sulphur and ash in the fuel, and the limestone required to flux them) would be as follows :

	Coke per Cent.	Charcoal per Cent.
Limestone required	27.5	3.175
Slag formed	28.4	3.33

The slag required approximately 25 per cent. of carbon to melt it.

= 7.1 per cent. carbon.

= 0.83 per cent. carbon.

Available carbon = 77.9 per cent.

Available carbon = 89.17 per cent.

The calculations were based on the assumption that the ash required twice its weight of limestone, and the sulphur 3.5 times its weight. Taking 16.5 cwts. of carbon as the average, as used by South Wales furnaces, that amount of carbon would be obtained from 21.2 cwts. of coke and 18.5 cwts. of charcoal, a difference of 2.7 cwts. per ton of iron in favour of the charcoal, based only upon the difference between the available carbon content in each case.

Slag Volume.—In a coke furnace the limit of the powers of the slag to hold sulphur was about 2 to $2\frac{1}{2}$ per cent., and in case of a charge containing 1.00 sulphur it seldom happened that less than 10 cwts. of slag per ton of iron could safely be produced, because the sulphur from the fuel was beyond what that volume of slag would absorb.

Charcoal furnace slags were more acid and fusible, therefore they had a lower melting point. Those slags contained as much as 45 to 50 per cent. silica. A slag of that kind could be carried, as there was practically no sulphur in the charge to be taken care of. The slag from a furnace using charcoal as fuel was smaller in volume than the slag from a coke furnace using the same ores. As the solubility of calcium sulphide in a siliceous slag was low, it was often necessary to increase the slag volume in order to carry the calcium sulphide in solution.

The solubility was raised by temperature and basicity, and both those facts were frequently increased to hold the sulphur. The carbon monoxide (CO) and carbon dioxide (CO₂) in the gas summed up to about 38 per cent., and that figure was fairly constant. If, therefore, there was a carbon ratio of 1.75/1 for a coke furnace, and a carbon ratio of 1.25/1 for a charcoal furnace, the composition of the gases would be :

Coke Furnace.				Charcoal Furnace.			
			Per Cent.				Per Cent.
CO ₂	:	:	13.8	CO ₂	:	:	16.9
CO	:	:	24.2	CO	:	:	21.1

Taking the value of CO at 360 B.T.U. per cubic foot, the gas from the coke furnace would give 87 B.T.U. per cubic foot, and the charcoal furnace 76 B.T.U. per cubic foot, a difference of 11 B.T.U. per cubic foot in favour of the charcoal furnace, due possibly to the higher combustibility and physical structure of charcoal. That really meant a reduction of about 2½ cwts. of fuel per ton of iron produced, which amount added to the 2.7 cwts., due to the purity of the charcoal, brought the consumption of charcoal to about 16 cwts. per ton, which was the usual amount found in practice.

He hoped the authors would be successful in any future research work that they might undertake, with a view to reducing the fuel consumption in blast-furnace practice.

Mr. H. NIELSEN (London) wrote that Messrs. Sutcliffe and Evans stated very definitely in their paper that they were not going to deal with the blast-furnace as a glorified producer, but in its primary function as an apparatus for the reduction of iron ore. It was all very well to draw attention to the possibility of fuel economy by the increased reactivity of coke, but he (Mr. Nielsen) suggested that not nearly enough stress had been laid on very obvious economies in other, and perhaps equally important, directions. He referred to the presence of hydrogen in the blast-furnace gas. Looking at the fuel economy question from a gas engineer's point of view, hydrogen in gas was always associated with a thermal loss in the fuel bed of any gas-producer. If the object in view were to produce hydrogen, fuel had to be expended, and it was necessary to rest content with that. On the other hand, if the object were not to produce hydrogen, there was no sense in wasting fuel on it if it could possibly be prevented. That the losses were very real would be evident from the following short calculation.

Selecting a blast-furnace gas at random from the authors' paper, Tables I. and II., No. 18, the gas had the following composition :

	Per Cent.
CO ₂	14.9
CO	23.5
CH ₄	0.2
H ₂	4.1
N ₂	57.3

The volume per ton of iron was equal to 120,800 cubic feet at normal temperature and pressure. Now, the hydrogen present in the gas could only be due to disassociation of water vapour, either by carbon direct or by the oxidising of reduced iron: in both cases a carbon loss ultimately occurred. What presumably took place could shortly be indicated as: $C + H_2O = CO + H_2$ —that was to say, that, without committing any grave error, one volume of H_2 produced an equal volume of CO. That reaction was strongly endothermic, and per cubic metre of mixed gases 650 kilogramme calories were required, which had to be provided by the fuel by complete oxidising.

The gas analysis showed 4.1 per cent. H_2 , hence another 4.1 per cent. by volume of CO could be said to be set free with the H_2 , or in all, 8.2 per cent. by volume of the total gas could be accounted for here, or = 9900 cubic feet = 283 cubic metres.

The total heat of formation of that quantity of gas was therefore $650 \times 283 = 183,950$ kilogramme calories. In the form of carbon consumed or reckoned as coke, containing 87 per cent. carbon, there

was $\frac{183,950 \times 100}{8080 \text{ kg. cal.} \times 0.45 \times 87} = 585$ lbs. of coke per ton of iron ore;

34.4 per cent. of the total coke consumption of 1699 lbs. Working backwards from the moisture originally contained in the air, namely, 5.5 grains per cubic foot, the moisture in the air required per ton of iron would only account for 2880 cubic feet of gas (50 per cent. CO + 50 per cent. H_2), or 82 cubic metres, which were equivalent to 170 lbs. of coke or 10 per cent. on the coke consumption shown.

The balance, namely, 24.4 per cent., was therefore due to moisture somehow or other, brought into the zone where the minimum reaction temperature of, say, 600°C. occurred. In all probability large lumps of moist ore, coke, and limestone were to blame for that. The heat penetrated only very slowly to the centre, so it was quite possible that when the heat got to the centre and gradually evaporated the moisture and the vapours escaped, externally the reaction conditions were already there, and the water vapours were decomposed.

The obvious cure was therefore to avoid moisture at all costs by:

- (a) Dry quenching of the coke.
- (b) Smaller lumps of raw material, so that ample time for drying was obtained before a critical reaction temperature was reached.
- (c) Dry blast.

It might be objected that smaller pieces required a more powerful blast. The answer to that was, that in gas-producer practice the smaller the fuel the more shallow the fuel bed, hence the blast pressure was practically unchanged.

As far as he (Mr. Nielsen) had been able to ascertain, it took from $1\frac{1}{2}$ to 2 hours for the raw material to pass down to a zone where the

temperature was above, say, 600° C. Under those conditions, and the prevailing temperature differences, the heat penetration would not be much more rapid than about 1 inch per hour, for coke, for instance, so it was evident that with pieces above 4 inches cube, the centre part was still comparatively cool and would retain moisture; or, in other words, only give the moisture up as vapour when the external temperature was well above reaction temperature. With larger lumps that was still more evident, so it would seem that the justification for smaller lumps was fairly well proved.

Messrs. SUTCLIFFE and EVANS, in a written reply, stated that in so far as Mr. Brownlie's remarks were concerned, they agreed with him that it was of national importance that as much as possible of the coal used in the country should be carbonised. It was now proved that a high-class smokeless fuel could be produced by high temperature carbonisation, and the production of that fuel should be undertaken by the great carbonising industries of the country—the gas and coking industries. In so far as costs were concerned, the following outline particulars might be of interest:

Preliminary Charges.

	<i>s.</i>	<i>d.</i>
10 h.-p. hours per ton for grinding at $\frac{3}{4}$ d. per h.-p. hour	0	7 $\frac{1}{2}$
5 " " briquetting at $\frac{3}{4}$ d. per h.-p. hour	0	3 $\frac{1}{2}$
Labour	0	6
Wear and tear	1	4
Depreciation and interest	0	9
	<hr/>	<hr/>
	3	6

Carbonising Charges.

Labour and supervision	1	0
Capital charges	2	6
Wear and tear, power water, steam, stores, &c.	1	6
	<hr/>	<hr/>
	5	0
Total costs briquetting and carbonising, including capital charges (per ton) .	8	6

The power consumption in the processes worked out by them was certainly high, but on the other hand the saving in capital and labour costs for the complete plant justified the expense of preliminary treatment.

With reference to the possibility outlined by Mr. Foster of the gases in charcoal protecting it from solution, the authors put forward certain experiments and results which did not support this view. Beyond that it was impossible to go at the present time, and they could only modify their views if experimental evidence could be produced by Mr. Foster to show that such protective action did occur. Up to the present the weight of evidence was against that hypothesis. Mr. Foster's views respecting the action of fusible ash in charcoal were interesting. The point had also been raised by Mr. Clements, and it was certainly worth while following up.

With reference to Mr. Reese's remarks, they (the authors) were greatly interested to note that a fuel of high reactivity or high rate of combustibility was considered an advantage by blast-furnace men of to-day. Essentially the efforts of the authors were directed to the production of a coke as strong as blast-furnace coke with a high rate of reactivity. Charcoal was a fuel of high reactivity and also of a high degree of friability, and for that reason the dimensions of a furnace using charcoal were necessarily limited. They were of opinion that if charcoal could be employed in a modern coke furnace the results would not be economical, for the reasons advanced in their paper. Owing to its friability it would block up the air passages, channelling would occur, and proper access of the reducing gases to the ore would be interfered with. They would therefore expect to find a higher fuel consumption than in a furnace of more suitable dimensions.

Modern coke furnace economy had been secured by increasing the dimensions and rate of driving of the furnace. That was possible owing to the coke being strong enough to support the burden without undue abrasion. Was it therefore not legitimate to deduce that if charcoal could be produced of a strength sufficient to permit of its use in furnaces of larger dimensions it would result in even greater economy than was now secured in small charcoal furnaces?

In the past a reactive coke had also been friable, and as reactivity went side by side with solubility in carbon dioxide, the accepted theory had been that such a coke was bad, not merely because it was friable, but because of its solubility in carbon dioxide. The authors' contention was that whilst friability should be condemned, solubility in carbon dioxide was a decided advantage.

In asking "Why the authors asserted that soft friable fuel, or a fuel that was easily acted upon by carbonic acid gas, could not result in any loss of fuel if the reaction took place in the upper part of the furnace," Mr. Reese was confusing the authors' contention. They were not champions of a "soft friable fuel," but they contended that a fuel readily acted upon by carbon dioxide gas would not be acted upon in the upper part of the furnace, for the reason that the carbon dioxide mixture would have attained equilibrium conditions down in the furnace where the temperatures were round 750° to 800°, and where the reaction on the ore would be as follows:



That reaction would leave the gas mixture practically in equilibrium with the fuel when the short time contact was considered.

The point raised by Mr. Reese with reference to the method of charging in layers was interesting, and was quite in agreement with the general conclusions of the paper. The authors did not claim that direct reduction took place between the carbon and the ore, but that it would result through the intermediary action of carbon dioxide, as explained on pp. 66 and 67.

Some of the results summarised on pp. 68 and 69 relating to the effect of coke reactivity on the carburisation of iron, had been obtained when the coke and iron had not been in direct contact, and it had been proved that reactivity of the coke played a very important part even when direct contact did not exist.

When the ore and coke were charged in layers, the coke had the effect of spreading out the gases and bringing them into more active contact with the ore. When the ore and coke were charged together the ultimate effect would be a splitting up and swelling of the ore which would choke up the passages, resulting in channelling and consequently in reducing the efficiency of a reduction. The particulars quoted by Mr. Reese helped to confirm the view that channelling, due to friability, was the real reason for the poor results obtained from a soft friable fuel.

Mr. Hutchinson had raised a rather interesting point in connection with the elimination of water from the coal by flotation. That question had been dealt with successfully by one of the authors (Mr. Sutcliffe), and it had been shown that water elimination prior to briquetting could be quite successfully effected by a modification of the briquetting press with which his name was associated.

The announcement made by Mr. Clements opened up some far-reaching possibilities, and further information would be eagerly awaited. In the meantime they were very interested to note that the purely theoretical conclusions advanced by them as to the possibilities of fuel reduction in pig iron manufacture had been confirmed in so remarkable a manner. A point raised by Mr. Clements with reference to charcoal furnaces and the degree of fusibility of the ash was very important. Essentially, expressed in Johnson's phraseology, it meant that the critical temperature in the charcoal furnace, owing to the fusibility of the ash, was very much lower than that of a coke furnace. That point had already been raised by Mr. Foster in discussing the influence of alkalis on the fusibility of the ash from charcoal. It would be interesting, however, to work out the total proportion of alkalis in the slag from a charcoal furnace working with an ore containing an appreciable amount of gangue. Perhaps Mr. Foster might take up that question with a view to ascertaining what would be the reduction in melting point of the slag thus produced. In any case the suggestion emphasised the importance of reducing the critical temperature in the furnace or, alternatively, to increase the available heat at the hearth for other reactions.

With reference to Mr. Ridsdale's remarks in connection with Cleveland ore, the possibility of reducing that ore with 12 cwt. of coke had been put forward by the authors in a paper to the Society of Chemical Industry (vol. xli. No. 12, p. 270). In putting forward the suggestion they stated:

"Taking everything into consideration, however, they do not think their suggestion that Cleveland ore may be smelted with 12 cwt.

of coke is such a dream as it may seem at first sight. It may be necessary to subject the ore to a suitable preliminary treatment, it may be necessary to reduce the ash in the coke to a figure considerably below that of existing practice (and both of these proposals are now receiving very serious consideration), but even if they are necessary, the economies involved are so considerable as to make this whole question of the structure of fuels a matter of immediate and vital importance to the iron and steel industry."

From the above quotation it would be seen that the possibility of preliminary treatment of the ore had been realised from the outset. As a matter of fact, the authors had drawn up several thermal balance sheets taking into consideration the possibilities outlined in the paper of using Cleveland ore, but with the high percentage of gangue now associated with Cleveland ore, they could not get a figure below 12 to 14 cwt. of coke per ton of iron. They believed, however, that even with the present type of Cleveland ore, the use of a reactive coke would result in a considerable fuel reduction.

With reference to the results quoted by Mr. Ridsdale regarding the increased consumption of fuel with Gellivara ore, that was a magnetic ore and reduction would take place to a greater extent in the hearth. Owing partly to the heat-absorbing character of direct reduction, and partly to the cooling action of the slag in accordance with the suggestions outlined on pp. 69 and 70, that would probably result in a considerable cooling of the hearth, and with an ordinary coke the final reduction would be difficult. With a reactive fuel, however, it would be possible to supply sufficient heat to balance the loss of heat produced by the above causes, and thus allow reactions to take place under conditions which would ultimately effect a saving of fuel. In that case again it was essentially a question of increasing the available heat in the neighbourhood of the hearth. With ordinary coke a considerable excess would be required to raise the hearth temperature to the necessary degree, whereas with a reactive coke theory pointed to the view that that excess would not be necessary.

Mr. Adamson's suggestion of testing a reactive coke in a small charcoal furnace was a very pertinent one, and when a sufficient quantity of the material was available, the authors hoped to be able to follow up this question.

Points of importance were raised by Mr. Hewson when he emphasised the influence of the time factor upon the chemical reactions in a blast-furnace. Some work had been done in that direction, particularly by Boudouard, but there was room for a considerable amount more of experimental work on the point.

Mr. T. D. Morgan's reference to Belani's work was very interesting, as the authors had considered that work very early in their studies on the subject. Later work, however, had shown that the matter was much more complicated than appeared at first sight. The same unit of carbon, whatever form it was in, produced the same quantity

of heat and required the same quantity of oxygen for combustion. In a blast-furnace, however, the heat in the hearth was not produced entirely by the combustion of the carbon, as a large quantity of heat was added by the heat contained in the burden, by the heat in the blast, and by other heat-producing reactions in the hearth, while from that sum total could be taken the heat in the slag, in the molten iron, and the sensible heat of the gases leaving the hearth. It was fairly obvious that if the source of loss in the hearth heat could be reduced either by reduction in the slag temperature or volume, or reduction of the temperature and volume of the gases leaving the hearth, there would be more heat available for the hearth reactions. In that connection his analysis of the results in charcoal and coke furnaces were interesting. The authors did not agree, however, that the usual consumption of 16 cwts. of charcoal per ton of pig was a true measure of the possibilities with charcoal. In numerous cases with charcoal furnaces that figure had been greatly improved upon, but one of the difficulties with charcoal was that its friability did not permit of results commensurate with its reactivity being obtained.

Mr. Nielsen's remarks relative to the effect of hydrogen in blast-furnace gas were very interesting. The authors, however, did not think it was quite justifiable to attribute the whole of the hydrogen to the dissociation of water vapour; a considerable proportion was due to the hydrogen in the coke. Most blast-furnace cokes contained 1 per cent. of volatile matter, the bulk of which was hydrogen. Assuming that the whole of that volatile matter was hydrogen, then on being heated in the furnace every 100 parts of coke would yield 11.11 volumes of hydrogen. On the other hand, every 100 parts of carbon would give roughly 185 volumes of oxides of carbon. Essentially then, if all other influences were omitted the relative volume of hydrogen and carbon gases from the coke would be something less than 1 is to 16. In the calculation shown by Mr. Nielsen, the relative volumes of hydrogen and oxides of carbon were as 1 is to 9, so that a proportion only of the hydrogen was due to the dissociation of water vapour. Even after allowing for the hydrogen in the coke, the calculation was a rather startling one, and the suggestion put forward by Mr. Nielsen was worthy of very serious consideration.

The calculation was of interest when compared with the analysis given by Johnson¹ of the effect of drying ore in a charcoal furnace.

¹ "Principles, Operations, and Products of the Blast-Furnace," p. 49, *et seq.*

Iron and Steel Institute.

BRITISH STEELWORKS GAS-PRODUCER PRACTICE.

By FRED CLEMENTS, M.INST.C.E., M.I.MECH.E. (ROTHERHAM).

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GENERAL NOTES AND DEFINITIONS.

Temperature.—Temperatures are given in centigrade units. Thermal calculations are worked from 15° C. as a base. Normal temperature and pressure for gas volumes are taken as 15° C. and atmospheric.

$$15^{\circ} \text{C.} = (15 + 273) = 288^{\circ} \text{C. absolute.}$$

Unit of Heat.—The centigrade heat unit is used. One C.H.U. is the amount of heat required to raise 1 lb. of water through 1° C.

Weight.—One ton = 20 cwts. = 2240 lbs.

Mean Specific Heat.—The formulæ used for specific heat give the mean values between 0° C. and T° C.

For example :

Mean specific heat of air = $0.2336 + 0.0000207 T$;
then at 1000°C . :

$$\text{Mean specific heat} = 0.2543.$$

This value is the actual specific heat at 500°C ., but is also the mean value applicable only to a change from 0°C . to 1000°C . If the change in temperature be, for instance, between 600°C . and 1000°C ., then the mean specific heat

$$\begin{aligned} &= \frac{1}{2} \{ \text{actual specific heat at } 600^{\circ} + \text{actual specific heat at } 1000^{\circ} \} \\ &= \frac{1}{2} \{ [0.2336 \times (0.0000414 \times 600)] + [0.2336 \times 0.0000414 \times 1000] \} \\ &= 0.2336 + [0.0000207 \times (600 + 1000)]. \end{aligned}$$

\therefore Mean specific heat between temperatures T_1 and T_2

$$= 0.2336 + 0.0000207 (T_1 + T_2).$$

This applies to all the formulæ used.

Mean Specific Heat of a Mixture of Gases.—The formula for a mixture is calculated from the specific heats of the constituent gases according to their respective percentages by weight.

Calorific Value.—In all cases what is usually known as the higher calorific value is taken. The lower calorific value is purely arbitrary and is not technically correct. The higher value is that comparable with the usual calorimeter results.

Moisture in Blast.—The term "steam" is used to describe that water vapour which has been raised under pressure in some external plant and is added to the air-blast. The moisture in the blast includes the hygroscopic content of the air in addition to the steam.

At the Annual Meeting of the Institute in 1922 the author had the privilege of reading a paper entitled "British Siemens Furnace Practice," and in that work he had confined himself to a study of the furnace only, taking the producer-gas as delivered at the furnace regulating valve as the basis of heat supplied. Naturally an investigation into gas-producer practice was necessary in order to complete the previous work. Such a survey is therefore the purpose of the present paper, with the object of elucidating how closely it is possible to approach, in the commercial operation of a steelworks gas-producer, to those results which are usually accepted as a scientific basis of producer practice, and also to compare the data so obtained with that supplied by other steel-making firms. Particularly it is intended to show impartially, from an operator's point of view, the relative merits of the non-mechanical and mechanical types of producers as used by the firms co-operating in this investigation. Considerable test work has been carried out on one of the three producers used in conjunction with one of the 60-ton Siemens furnace units of the Park Gate Iron & Steel Co., Ltd., and the data

obtained have been used to form a basis for technical comparison. The producer is of an old type which has been revised from time to time, as suggested by experience, in order to adapt it to the conditions of work. It is admittedly not without faults from a scientific standpoint, yet it is used for the purpose indicated with confidence, in view of the increasingly good results which have been obtained in the furnace practice for a number of years past.

It was determined that, as far as possible, all the data obtained should be quantitative, and therefore special arrangements were made to obtain accurately the following particulars by direct measurement :

- (a) The quantity of air blown into the producer.
- (b) The quantity of steam used.
- (c) A constant steam saturation temperature.
- (d) A definite height of fuel bed.
- (e) Gas analyses which should represent average conditions.
- (f) The moisture, tar, and soot contents of the gas on leaving the producer.
- (g) The temperature of the outgoing gas.
- (h) The weight of coal charged and average samples for analysis.

In addition to the foregoing information the pressure was obtained at various points in the producer system, and also the amount of steam condensed in the blower-box was carefully measured and deducted from the gross amount, so that the actual weight of steam entering the fuel was correctly ascertained.

The arrangement of the testing apparatus is indicated in the sketch on Sheet No. 1. For the measurement of the air a Pitot tube together with a curved tube manometer was used, and for the steam an orifice type direct reading meter. Both these instruments were bought from Messrs. George Kent & Co., Ltd., of Luton, and were guaranteed accurate to within 0·5 per cent. They were sensitive to the slightest change in conditions, and were in every way satisfactory.

The coal was carefully weighed in a specially constructed box before being charged into the hopper, and the times of charging carefully noted on the log sheet. The gas samples for analysis, as well as those for the determination of the tar, soot, and

moisture contents of the gas, were obtained from the producer outlet neck. The apparatus used is shown and described on Sheet No. 1. A testing staff was organised, and series of tests under different conditions of saturation temperature and depth of fuel bed were carried out. As the tests had naturally to be made without interfering with the work of the furnace, it was not possible to test the effect of any systematic alteration of the rate of gasification, but some difference naturally arose owing to the different conditions which obtained between one test and another. Readings were taken every five minutes, and logged on specially prepared sheets, and the results for each test were carefully averaged. The particulars of the producer are given on Sheet No. 6. It will be observed that its construction is of the simplest character. The advantage of this will be appreciated, since units of this description have been in operation for five years without any cessation of work for repairs. Special care is taken to prevent any wastage of gas. The coal hoppers are closed by means of machined lids, and patent steam-blown poking holes are used, so that the attendant can attend to the condition of the fuel bed without any loss of gas, and at the same time without personal discomfort. It should also be noted that this device enables him to see the fuel bed during the process of poking, and therefore ensures more thorough carrying out of the work.

The synopsis of the paper is as follows :

1. A consideration of the chemical and thermal balance in a producer with the same saturation temperature but different depth of fuel bed.
2. A consideration of the chemical and thermal results effected by varying the saturation temperature when using fuel beds of different depths.
3. A consideration of the detailed schedules of British steelworks gas-producer practice along with information calculated from the data.
4. A consideration of the arrangement of a producer plant of the non-mechanical type, and that of a plant of the mechanical type, each designed for similar capacity and conditions of service.
5. A consideration of the comparison of capital cost, labour,

and maintenance on the two plants indicated in (4), and the determination of the cost of gasification in each per 1000 tons of coal charged, under the most modern conditions.

The very sensitive nature of the conditions obtaining in the chemical and thermal interchange in progress in a gas-producer is one of the first facts which is impressed on the investigator. Whilst every care was taken in arranging the tests so as to eliminate, as far as possible, unknown variables, it was found necessary to repeat some of the tests several times before anything like conclusive figures were obtained. It is important that gas-producer users should appreciate this point, since it appears, out of the experience which these systematic tests have provided, that a very much closer and more scientific supervision is necessary than is usually accorded to this important section of steelworks equipment. The financial return in resulting economies will make any outlay in this direction a profitable investment.

CHEMICAL BALANCE-SHEET.

The chemical balance-sheet for the 5 feet fuel bed is shown on Sheet No. 2, and for the 3 feet 6 inches fuel bed on Sheet No. 3. These will be self-explanatory, and need little discussion. The figures are the averages obtained during the test, and are given on the basis of one hour's work. The amount of steam decomposed is more with the 5 feet fuel bed (57·5 per cent.) than with the 3 feet 6 inches bed (47·2 per cent.), but in each case a considerable amount of the usefulness of the steam lies in its thermal influence as a cooling medium rather than in its chemical effect by decomposition. This point is borne out strongly by the series of tests shown on Sheet No. 4.

THERMAL BALANCE-SHEET.

The heat balance of each set of conditions shown on Sheet No. 2 and Sheet No. 3, respectively, is also self-explanatory. There is, however, the difficulty of stating the efficiency of a producer on some equitable basis. The hot-gas efficiency is the

value which is the most technically correct, considering a producer as a thermal machine, and in many types of furnaces where the sensible heat carried is usefully employed this efficiency can be taken as most nearly representing practical conditions.

In the case, however, of a furnace where the gas passes through regenerators the sensible heat carried is not of any great advantage—indeed it precludes the use of gas regenerators of the most efficient design, since it is not economical to reduce the temperature of the chimney gases during recuperation below that of the producer-gas which will be admitted during regeneration. At the same time, to adopt the cold-gas efficiency as the basis is equally incorrect since, if this be rigidly adhered to, it ignores the value of the tar mist and the finely divided carbon which are always carried with the gas, and have an important bearing on the metallurgical value of the resulting flame. It is difficult to decide on the correct view to take as to the influence of the finely divided carbon, or soot, on producer efficiency, since some of it settles in the flues and therefore never reaches the furnace. There is also some proportion of the tar mist decomposed during the passage of the gas through the regenerators, but not to the degree that is often assumed. It is evident from the test made at Park Gate that the temperature ruling above the fuel bed in a producer is of the order of 800°C. , and therefore the tar mist remaining at that temperature is mainly of the higher series, probably of the naphthalene group. These are relatively stable compounds and do not easily decompose.

A number of tests made in connection with the present investigation, for the purpose of comparing the composition of the gas before entering the regenerators and in the uptake to the furnace, failed to show any appreciable difference in the analysis. With regard to the relative amounts of tar and soot present, it was found that whilst the weight of the tar carried had decreased owing to decomposition, the total weight of carbonaceous matter was only slightly reduced. It seems reasonable, therefore, in order to make a fair allowance to cover unknown circumstances, to credit the producer-gas with the whole of the calorific value of the tar mist and 80 per cent. of that of the soot carried in suspension as it leaves the producer. The remainder can be taken as lost in the flues and chambers.

It is recommended that a value for furnace gas efficiency should be adopted. This is determined as follows :

$$\text{Furnace gas efficiency} = \frac{\left\{ \begin{array}{c} \text{Calorific value of the cold gas} \\ + \text{calorific value of tar} \\ + \text{calorific value of 80 per cent. of soot} \end{array} \right\}}{\text{Total heat carried into the producer}} \times 100.$$

This expresses the value on a comparative basis applicable to any type of producer, and, in passing, it might be noted that the ordinary gas analysis is of little quantitative value unless the amount of tar mist and soot carried is determined at the same time and allowance made for it, as the effect of these is to increase the actual calorific value of the gas by an amount roughly equal to 10 per cent. of the calorific value of the cold gas. The series of tests scheduled on Sheet No. 4 were carried out with a view to investigating the effect of varying the steam saturation temperature with fuel beds of different depths. The results are largely what would be expected from theoretical considerations, but it is significant that the advantage of the 5 feet fuel bed over the 3 feet 6 inches bed is not very marked. The latter bed is, of course, much more easily worked from a manipulative point of view, and whilst the gas analyses and total calorific values for the deeper bed are a little the superior the difference is not very marked on the basis of furnace gas efficiency.

At 50° C. saturation temperature the temperature of the hot zone became so high as to be almost unworkable, and, even with the excellent coal used, trouble was experienced with the clinking of the ash, which involved additional poking. At the higher saturation temperatures, 65° C. and 70° C., the quality of the gas was reduced, and the amount of free moisture carried was excessive. The best results were obtained both in the producer and in the furnace when the saturation temperature was 55° C. It seems, therefore, that when working with coals of reasonably good quality a saturation temperature of 55° C. and a fuel depth of about 4 feet is a combination which can be relied upon to give satisfactory results both in efficiency and in easy operation.

Efforts were made to determine the temperature at different zones in the producer bed, but all failed, owing to the difficulty of getting any metal tube, for protecting the silica tube of the

pyrometer, to withstand the oxidising conditions and the high temperature developed in the hot zone. Test-bars were therefore employed, and from the observations made it was evident that, even at the higher values of blast saturation, the temperature attained in the hottest zone was greater than generally anticipated. Readings up to $1400^{\circ}\text{C}.$ were observed at $55^{\circ}\text{C}.$ saturation temperature during the efforts to obtain the temperatures previously referred to. Gas samples were taken at the levels corresponding with those at which the temperatures were to have been obtained, but the results are not included in this investigation, as further experimental work is necessary before this essentially interdependent information can be correlated.

From the data obtained, however, it would appear that the time element is an important factor in the establishing of chemical equilibrium at any zone, and therefore it follows that in a producer of correct design the blast should enter the fuel in such a fashion that it passes relatively slowly amongst the incandescent carbon, especially in the early stages.

Before considering the comparative data on Sheets Nos. 11, 12, and 13, it may be advantageous to review, from the point of view of the user, the various factors which go to make up the best type of gas-producing plant. They can be summarised as follows :

1. The quality of gas should be uniform, and that most suitable for furnace work.
2. The gas should be available at the furnace regulating valve at a constant pressure.
3. The producer should require the minimum amount of attention both in operation and in maintenance.
4. The loss of unconsumed carbon with the ash should be a minimum.
5. The total capital, labour, and upkeep costs should be a minimum.

These factors are dealt with in sequence.

Factor 1.—It is the Siemens melting furnace which is particularly concerned in this investigation, and consequently the quality of gas desired is that which most efficiently performs the functions required of it in steel manufacture. The functions are that the gas should burn vigorously, and that the rate of

transfer of heat between the flame produced and the materials in the bath should be a maximum. These conditions do not altogether depend upon the calorific power of the gas so much as on the radiating power of the flame, although in furnaces of modern design more advantage is now being taken of the contact of the burning gases with the metal. It is quite possible that a change in the gas composition which may result in a less calorific value may give a more efficient heat transfer in the furnace. Variation in the composition of the gas is only possible within relatively narrow limits, governed by the working conditions of the producer, but it is necessary to determine as far as possible what are the best conditions within those limits and to arrange for the producer practice to give the desired results.

There are four combustible bodies to consider, namely, carbon monoxide, hydrogen, methane, and tar mist. The relative values of the carbon monoxide and hydrogen as combustibles have been frequently dealt with, and in view of the higher radiating power of the CO flame it is evidently desirable to increase the CO content and decrease the H_2 content as far as practicable. In accordance with the theory of producer-gas manufacture, the increase in the amount of steam added to the blast results in an increase of hydrogen and a decrease in carbon monoxide, and this is fully borne out by the comparative tests shown on Sheet No. 4. It is therefore evident that the best results are obtained by working the producer at as high a temperature as possible, and with the lowest steam saturation value permissible. The methane and tar mist are both products of direct distillation, and depend more on the character of the coal used than on the working methods of the producer. Naturally a coal containing considerable volatile matter will give a higher amount of tar in the gas although, as previously indicated, the character of the tar will depend upon the temperature of its distillation, or, in other words, on the temperature of the upper layers of the fuel bed. Since these upper layers are hotter with a shallow fuel bed, it can be taken that the depth of the fuel bed is a factor in the methane and tar mist contents of the gas. The value of the tar mist is not only measured by the increase in the total calorific power of the gas, but chiefly by the fact that its presence

ensures the luminosity of the flame and therefore increases its radiating power.

A gas composition which would give very satisfactory results in a furnace is as follows :

	Per Cent.
Carbon dioxide	5.0
Carbon monoxide	28.0
Hydrogen	10.5
Methane	4.5
Nitrogen	52.0
Total combustibles	43.0

In addition, the gas on leaving the producer would carry in suspension about 15 grammes per cubic metre of tar mist, which if taken as naphthalene would have a formula of $C_{10}H_8$ and a calorific value of 9400 centigrade heat units per lb. ; also about 10 grammes of soot per cubic metre of gas.

The moisture carried with the gas can only have a secondary chemical effect in the furnace, and if such effects do occur they are mainly of a deleterious nature. The less the amount of moisture carried, therefore, the better is the result. The moisture in the coal undoubtedly enters the gas as vapour as soon as the coal is charged, and this is inevitable ; but it should be noted in passing that it is advisable for the coal used to be as dry as possible. The remainder of the moisture is therefore undecomposed steam, and this represents not only an undesirable adjunct to the gas, but also is a fuel waste, since the steam has been generated originally exterior to the producer. It is admitted, of course, that if a hydrogen content of only 10 per cent. is desired, then even at 55° C. blast saturation temperature only about 50 per cent. of the steam can be decomposed, and this entails the remainder passing into the gas as moisture ; yet it has had a thermal effect in cooling the incandescent bed of fuel as well as helping to disintegrate the clinker. Reference to Sheet No. 6 in the paper on "British Siemens Furnace Practice"¹ will show at once the considerable effect the moisture has thermally, as a result of its high heat capacity ; but this effect is strongly negative, and there would be a decided gain to the furnace if the moisture in the gas could be eliminated.

The conditions necessary for uniform results of the character just outlined are as follows :

¹ *Journal of the Iron and Steel Institute*, 1922, No. I.

(a) A fuel depth sufficient to ensure adequate contact between the gases and the fuel.

(b) The velocity of the gases to be low enough and the zone temperatures high enough to provide for the sufficiently long time of contact, and for the thermal conditions necessary to ensure chemical equilibrium.

(c) The use of fuel of proper size (graded between 1-inch and 2-inch mesh) evenly distributed, so that all parts of the bed work freely.

(d) The possibility of channelling of the gases through the burden to be provided against.

(e) The blast saturation temperature to be evenly maintained. Its value should be only just high enough to ensure the proper working of the fuel, whilst keeping the amount of undecomposed steam passing into the gas as moisture as low as possible.

Factor 2.—The amount of gas required during the progress of working a charge in a Siemens furnace varies, and consequently the furnace operator controls this with the regulating valve. If, however, the producers continue to generate gas at the same rate during the whole time it is obvious that, when the furnace is not taking the normal requirements, the pressure in the producer rises considerably, and the opposite effect occurs when the furnace is demanding the maximum amount of gas. Again, during a period of regular work it is distinctly advantageous for the furnace operator to be able to set his gas and air valves so as to give the combustion desired, and then to be confident that the conditions will remain unaltered. It is therefore desirable that the rate of production of gas should be directly and automatically governed by the gas pressure at the regulating valve, and means for controlling the steam and air inlet to the producer should be provided. If adequate provision is made at the producer no difficulty need arise in arranging for the control by the gas pressure.

Factor 3.—Naturally, in order to provide for a supply of gas of uniform quality, the conditions within the producer must be maintained uniform. Logically this emphasises the need for continuous feeding of the coal, even distribution over the whole of the bed, and automatic poking. It is admitted that the modern types of mechanically operated producers have been

designed with a view to achieving the ideal conditions outlined, and whilst this is done to a varying degree of success it must not be lost sight of that the attainment involves the use of considerable machinery, which is expensive in first cost and also requires maintenance. It is doubtful economy to reduce the charge for semi-skilled labour on the producer and replace this by a charge for skilled labour in repairs. It is a matter, therefore, for close investigation whether a non-mechanically charged producer, intelligently operated, is not a more economical installation in the final analysis of the cost of production. Again, reference to Sheet No. 12 shows that in general practice it is possible to get from a non-mechanical producer, when intelligently operated, gas of equal quality to that produced in mechanical units, and it may be worth while to sacrifice something of the ideal for the sake of lower production cost.

Factor 4.—The reduction of the loss of carbon with the ash to a minimum is not easy of attainment. The consideration only of the proportion of carbon in the ash is not sufficient to reveal the true loss, since the actual incombustible carried in the coal has a bearing on the matter. The loss of 5 per cent. of carbon in the ash from a coal containing 10 per cent. of non-combustibles represents a net loss per ton of coal charged equal to 10 per cent. of carbon in the ash from a coal containing 5 per cent. of non-combustible. This fact is frequently lost sight of, and the only useful comparison is the carbon lost per ton of coal charged.

The observations during the Park Gate tests on the different zones in the producer confirmed that the zone of highest temperature is immediately above the ash zone, and the transition from the one to the other is abrupt. If therefore a portion of the carbon is not entirely consumed during its passage through the hot zone and it enters the ash zone, there is little opportunity of gasifying it, since it becomes almost immediately submerged in inert material. It is conceivable, however, that the lower stratum of the hot zone is made up of a mixture of combustible and incombustible material, in which the latter is rapidly increasing in proportion. It is the action within this stratum which determines the amount of combustible that will be lost in the ash, and in order to provide the most favourable conditions

for the oxidation of the last remnants of carbon it is desirable that the stratum referred to should be blown with air only, and the moisture saturated blast should be introduced above it.

Ostensibly a producer provided with mechanical ash discharge should reduce to an absolute minimum the amount of carbon lost, but with many classes of coal there is a tendency for the bed to cohere in the upper regions, and experience shows that it is often necessary to resort to hand-poking to break down the burden, and when this is the case the loss of combustible is materially increased. Reference to Sheet No. 11 will show the general experience on this point.

Factor 5.—The choice of the means of producing gas lies between two systems, viz. an installation of non-mechanical producers or one of the mechanical type. In order to arrive at an effective comparison, a complete installation of each system has been designed for identical conditions of work. Both have been arranged with modern equipment for handling coal and ashes, and can be taken as representative of their respective types. The arrangement of the non-mechanical plant and that of the mechanical plant are on Sheet No. 14. For the latter the Kerpely producer has been taken as a representative type widely used in Great Britain, and the author is indebted to Messrs. E. G. Appleby & Co., Ltd., 70 Victoria Street, Westminster, London, S.W. 1, for their kind co-operation in preparing the drawings and supplying the data which have made the comparison possible.

The capital cost of each plant has been accurately obtained, based on present-day prices; that for the non-mechanical plant being supplied by Messrs. Markham & Co., Ltd., Chesterfield; Messrs. Appleby & Co., Ltd., having provided the cost for their own design. In view of the greater amount of machinery involved in the mechanical plant, an annual depreciation of 10 per cent. of the capital cost has been allowed, whereas in the non-mechanical plant $7\frac{1}{2}$ per cent. has been taken. This is deemed to be an equitable allowance.

The details of the cost of gasification per 1000 tons of coal are shown on Sheet No. 15, and from this it will be seen that the cost is slightly higher on the non-mechanical plant. In considering this, however, it should be noted that no allowance

has been made for incidental labour, and a reference to item No. 8 on Sheet No. 11 shows that on the various returns of operative practice hand-poking has to be resorted to on mechanically operated plant. The result of this is evidenced in the figures given in item No. 38, Sheet No. 13, where it will be observed that the labour cost of gasification per 1000 tons of coal is much the same as on the non-mechanical plants. It is not desired to press this as a point in favour of the non-mechanical plant, but it is one which it is necessary to consider closely. Possibly in each case there are special local circumstances which in some measure may account for the results.

Further, the question of the cost of repairs deserves attention, and whilst it is admitted that the latest designs of mechanical producers have been developed with a view to reducing the liability to mechanical failure, the service is of such a nature that the wear on the moving parts is likely to call for maintenance by skilled labour.

On Sheet No. 15 an effort has been made to state the advantages and disadvantages of each type of plant as impartially as possible.

In conclusion, the author trusts that the experimental and operating data, as well as the scheduled experience of present-day practice, may be useful in determining future policy. In view of the varying conditions of quality of coal and its differing physical character, it is impossible to outline any axioms which would be applicable to all cases. Each therefore must be examined in the main on its merits.

The author takes the opportunity to acknowledge the permission given by Mr. Charles Markham, the Chairman of the Park Gate Iron & Steel Co., Ltd., to carry out this investigation, and to appreciate his interest in it.

Sheets Nos. 6 to 13, inclusive, have been compiled from data supplied by the firms whose names occupy the heads of the columns. Thanks are due to these firms for the ready way in which they co-operated in supplying the information.

The author also acknowledges the help he has received from his colleagues and friends of the Park Gate Company, and particularly that rendered by Mr. W. S. Allen, A.M.I.Mech.E.,

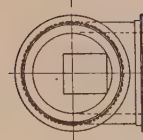
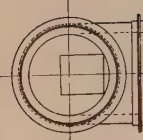
and Mr. T. P. Colclough, M.Sc., who were responsible for the detail work in the organisation and carrying out of the producer tests. Mr. Harry Williams assisted materially in scheduling the information.

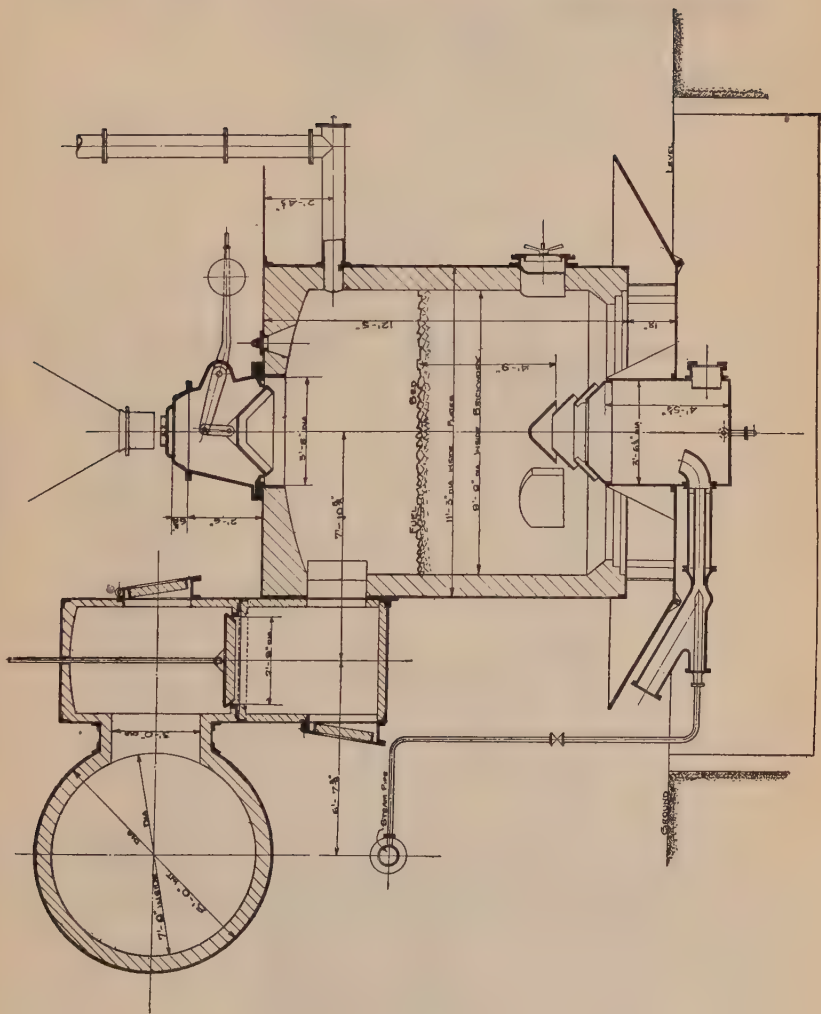
From his brother, John A. Clements, F.I.C., the Chief of the Chemical Section of the Brown-Firth Research Laboratories, the author has received invaluable aid in formulating the arguments in the paper as well as in the analysis of the data.

Sheets Nos. 1 to 4 and Sheets Nos. 11 to 15 are inserted as folders.

Sheets Nos. 5 to 10 are contained in the pages immediately following.

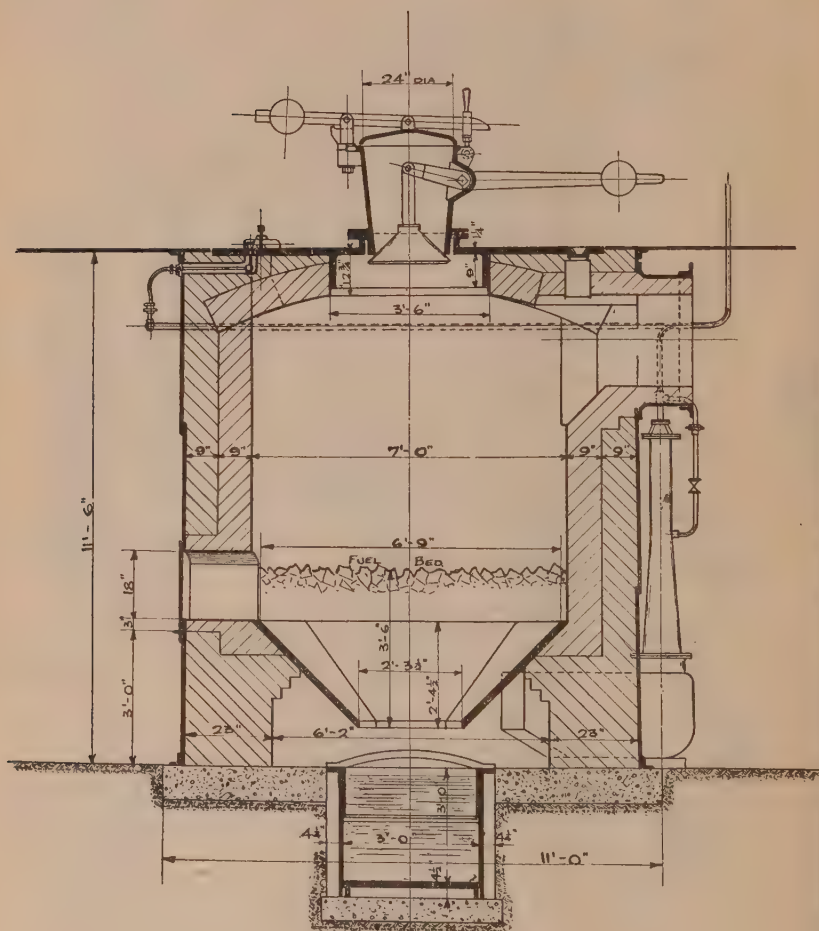
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BRYMBO STEEL CO. LTD.
WREXHAM**



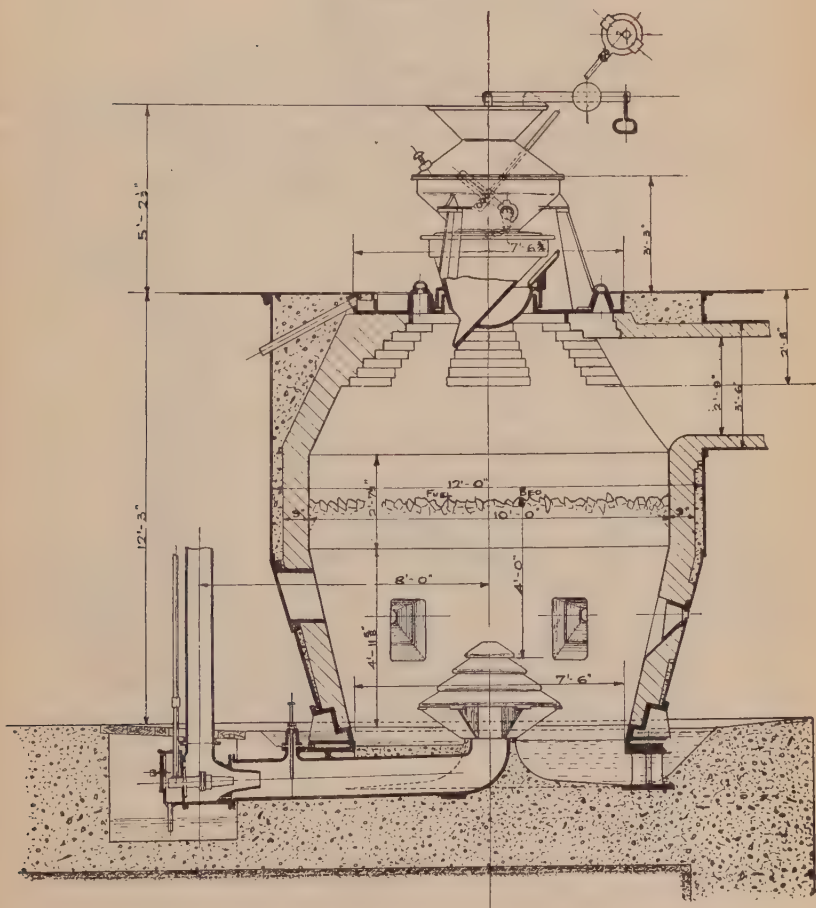


NON-MECHANICAL

THE IMPROVED WILSON GAS PRODUCER PARK GATE IRON & STEEL CO LTD ROTHERHAM

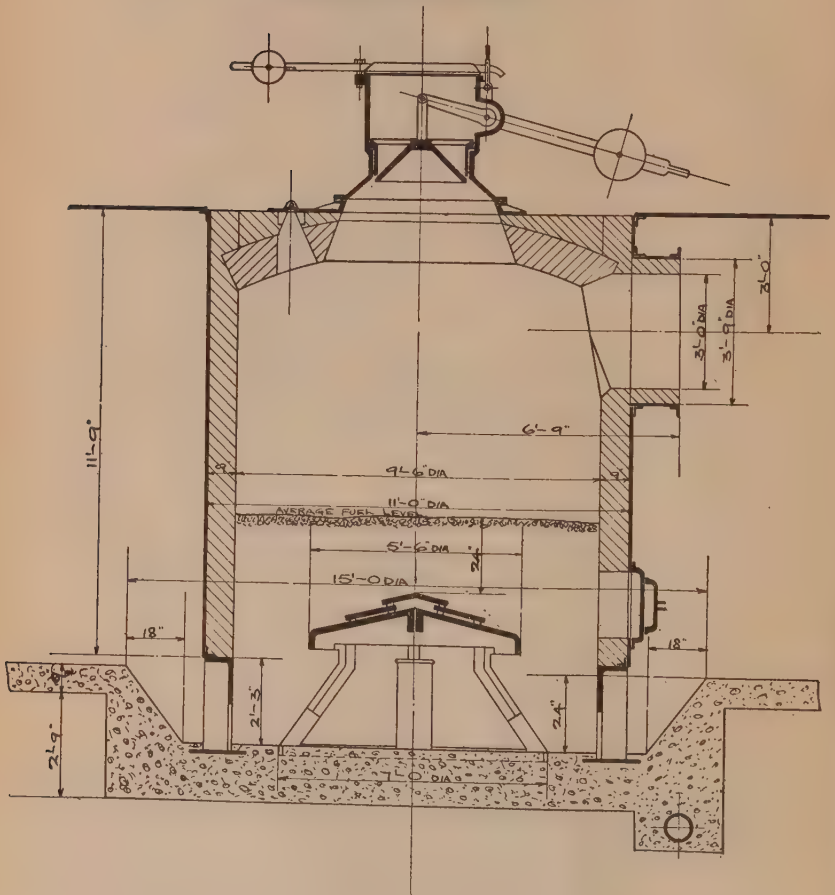


THE MORGAN GAS PRODUCER
WITH "GEORGE" FEED
WILLIAM BEARDMORE & CO LTD
MOSS END STEEL WORKS
LANARKSHIRE



NON-MECHANICAL

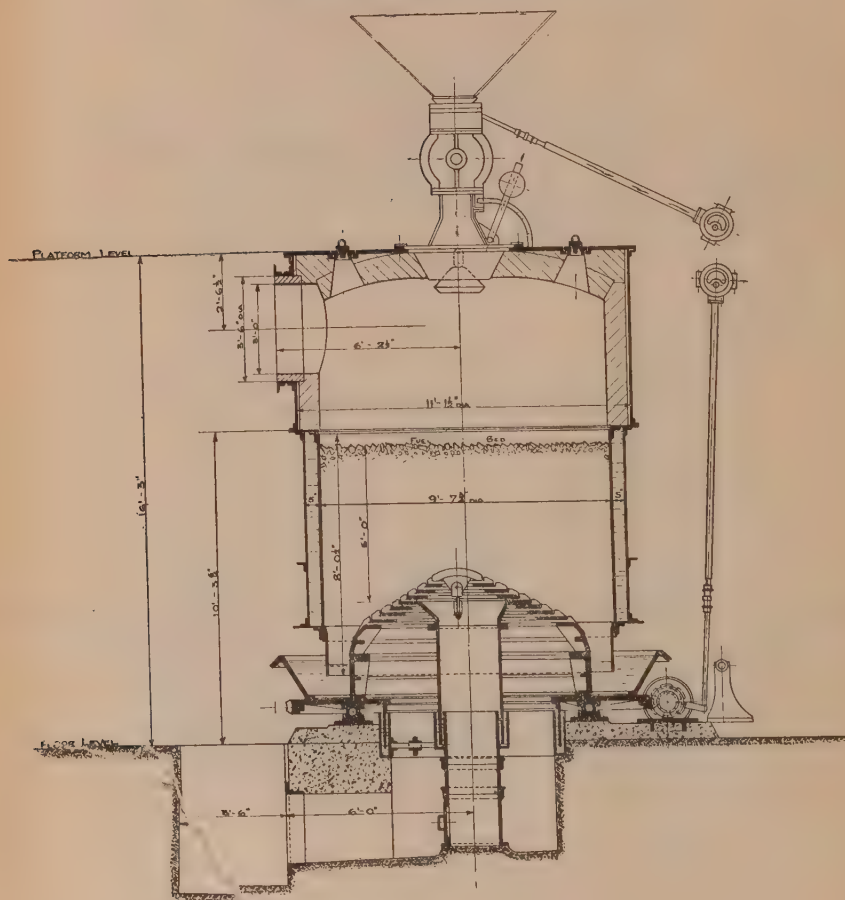
DORMAN, LONG & CO. LTD.
MIDDLESBROUGH



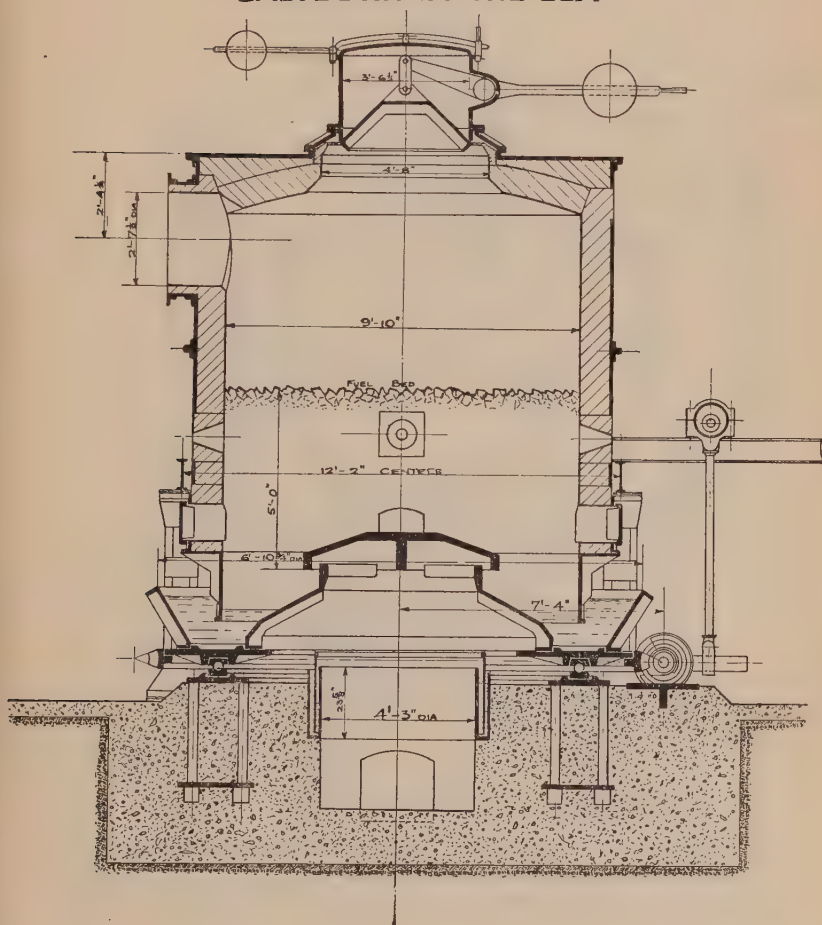
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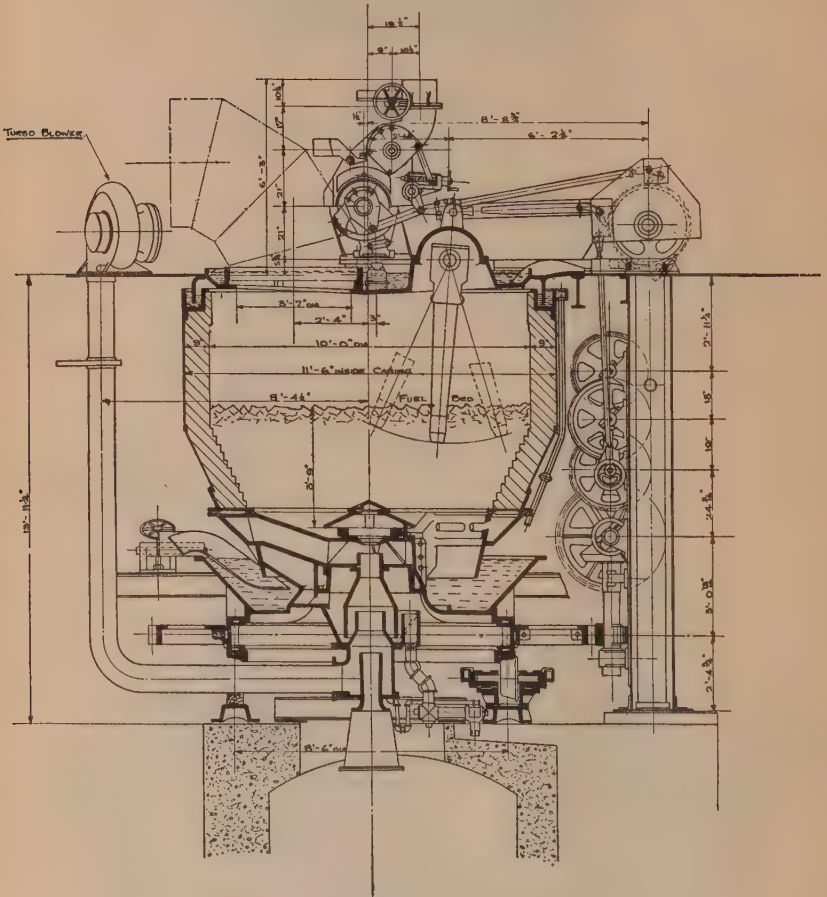
THE KERPELY GAS PRODUCER SKINNINGGROVE IRON CO. LTD. SALTBURN BY THE SEA



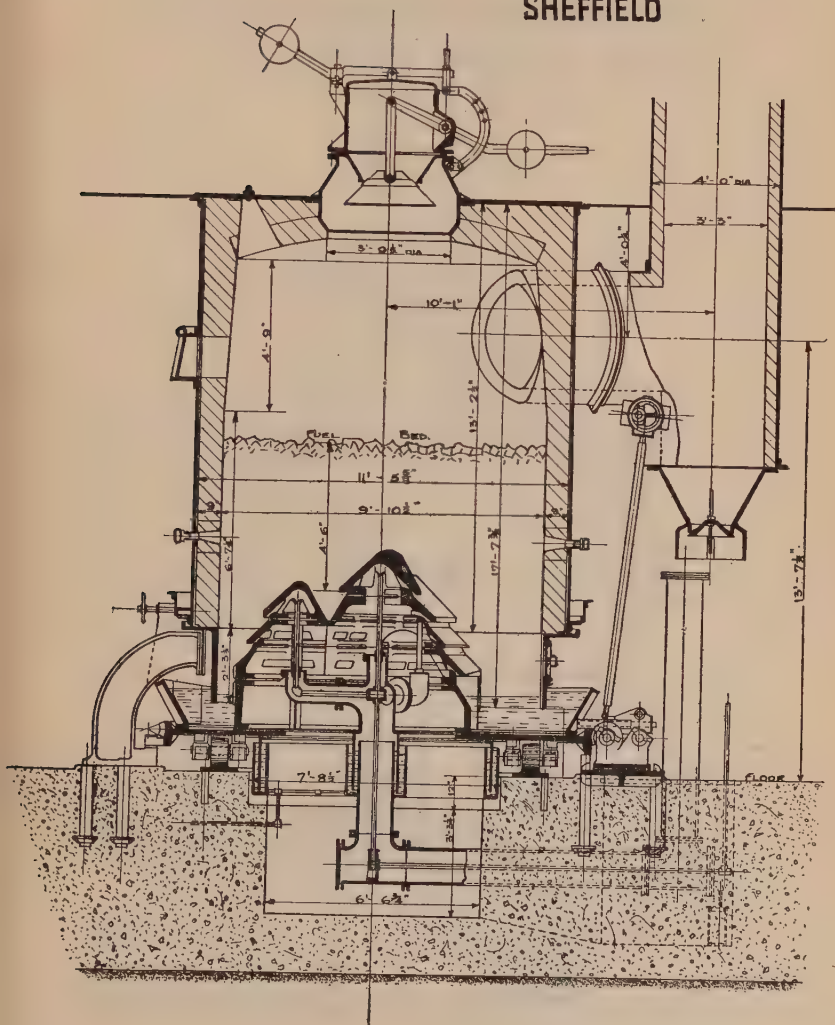
**THE HILGER GAS PRODUCER
SKINNINGROVE IRON CO. LTD.
SALTBURN BY THE SEA**



THE HUGHES GAS PRODUCER THE BETHLEHEM STEEL CO. U.S.A.

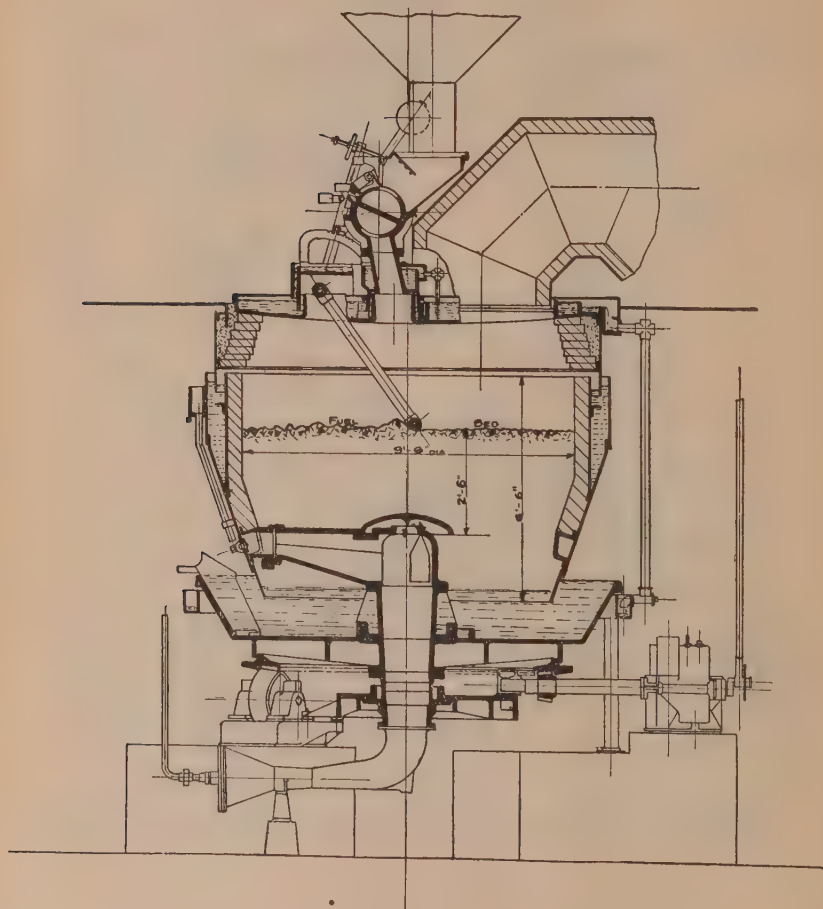


THE REHMANN GAS PRODUCER VICKERS LTD. SHEFFIELD

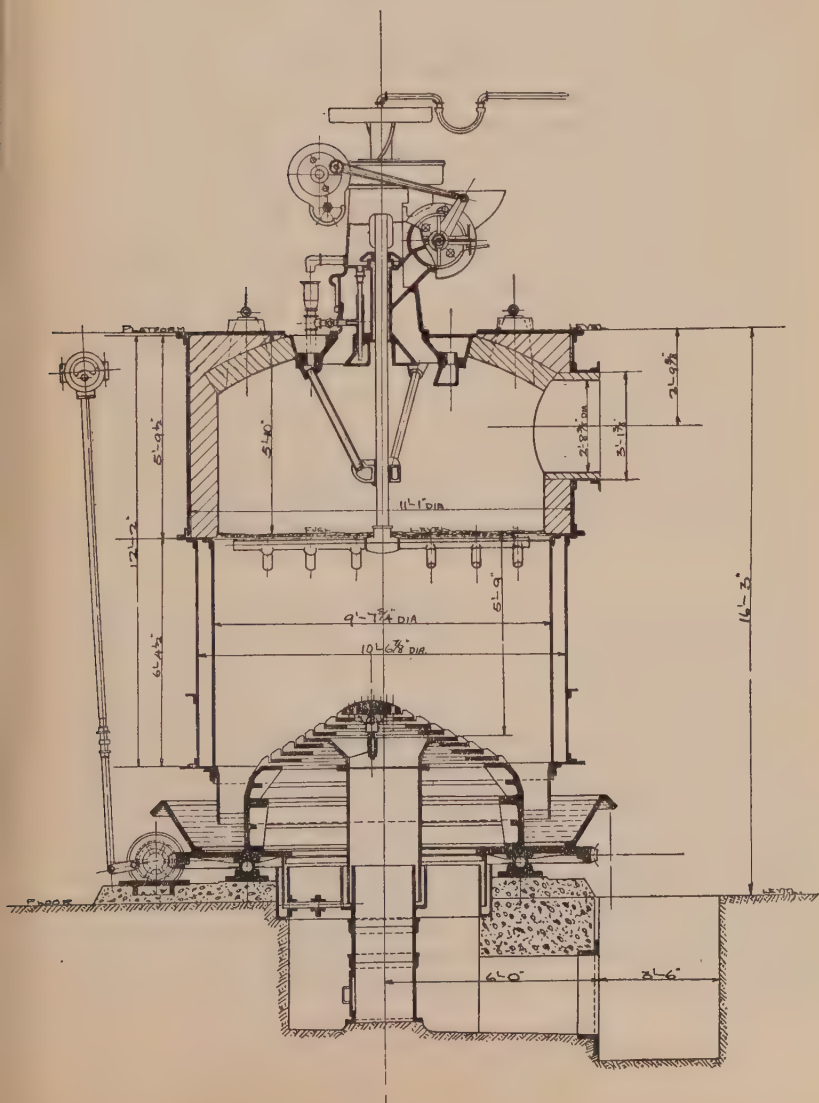


MECHANICAL

THE MORGAN GAS MACHINE STEEL PEECH & TOZER LTD. SHEFFIELD



THE KERPELY GAS PRODUCER
WITH CHAPMAN AGITATOR
SHELTON IRON STEEL & COALCO LTD
STOKE-ON-TRENT



DISCUSSION

Mr. H. M. RIDGE (London) said Mr. Clements had repeatedly drawn attention in his paper to the question of undecomposed steam passing with the producer-gas into the furnace. That steam was obviously detrimental because it did no useful work in the furnace; on the contrary it absorbed heat, and in addition coal and boiler capacity were required to obtain that steam. The only useful effect that could be claimed was perhaps that it cooled the producer. The main point which he would like to submit to the meeting in connection with this paper was the consideration that a better method was available for blowing air into the producer. He thought that probably everybody concerned with producer practice had in the past tried the effect of increasing the amount of steam blown into the producer, but so far as he was aware the results were not happy. He had also carried out many investigations in the other direction, and the results showed him that it was desirable not to rely upon steam—in other words, to replace the steam with a blower and to add the necessary and requisite amount of moisture to avoid the formation of clinker. He thought that was the main argument that had to be considered. Steam or water vapour should only be used to reduce and prevent clinkering, and it did not otherwise perform any useful function. He had not succeeded in reducing sufficiently the steam passing into the producer where it was used alone for blowing; he had only succeeded in reducing the steam consumption by using an auxiliary blower, but by installing the blower and then moistening the air with the necessary amount of steam he found he could obtain the most satisfactory results.

He hoped Mr. Clements would give fuller information as to the method he adopted for determining the moisture contained in the producer-gas. He personally had experienced a good deal of trouble in that respect in the past.

Mr. BENJAMIN TALBOT, Member of Council, said that as usual the members had had the pleasure of hearing a very valuable paper from Mr. Clements, but he (Mr. Talbot) did not altogether like Mr. Clements' conclusions. Reading between the lines he rather gathered he did not think there was much in the mechanical producer plant. As one who had had the pleasure of collaborating with the late Mr. Hughes at Pencoyd, and had been responsible for the introduction of that producer, he would like to point out the reason why it was adopted. It was because, even in America, it had been found that the fuel was getting worse at that date. It was also found that labour was becom-

ing more unsatisfactory, and those were the chief reasons why the development of that plant was investigated and adopted at Pencoyd in 1898.

In looking through the description of the fuels which Mr. Clements had been fortunate to use at Park Gate, he came to the conclusion that he would never have gone into the development of the mechanical producer plant if he had been supplied with the same kind of fuel, and it was there he thought that Mr. Clements was wrong in his comparison, namely in showing only a little difference in favour of the mechanical plant as against a well-designed hand-worked plant. For actual comparison some of the fuels that had to be dealt with in Durham, with at least 20 per cent. of ash and of a very swelling character, should be taken. It would then be seen how the old hand-worked plant would compare with the mechanical. At the works with which he was concerned they had mechanical producers, a development of his own, which had been perfected very slowly, because it had taken them ever since 1898 until a few years ago to make a satisfactory mechanical plant. Still there was never much in that, because they had had a somewhat similar experience in designing open-hearth furnaces. He thought if they looked into the poor fuel conditions under which many had practically to work, they would find there was a great superiority in regard to the mechanical plant as compared with the old hand-working type. Personally he hoped it would not be many years before they saw no mechanical plants at all. That was a state of affairs which perhaps was to be expected. They wanted to do without them, and if it came to pass that they were going to save more fuel at the blast-furnaces he did not know whether they would benefit very much in regard to steel-works, but probably they would get more coke-oven gas. That was the kind of fuel he hoped they would use largely in their steel furnaces in the future.

Mr. F. W. HARBORD, C.B.E., Member of Council, said he thought Mr. Talbot had summed up the position that the mechanical producer versus the hand producer was very largely a question of the particular kind of coal they were using. If it were required to use a coal which was a coking coal, and in addition to that contained a substantial proportion of ash, the difficulty of efficiently poking hand-fired producers so that a regular gas was produced was, if not insurmountable, at any rate extremely difficult. In such circumstances the advantage of a mechanical producer was obvious. Like Mr. Talbot, he (Mr. Harbord) was personally looking forward to the time when it would be possible to do away with producers, but he was afraid that was a long way off. If the kind of fuel suggested were to be used in blast-furnaces he thought Mr. Talbot would be worse off, because he would have less coke to make in his coke-ovens, and he would consequently have less gas to use in his steel furnaces.

Mr. W. H. PATCHELL (London) said he had been responsible for some time for a 60-ton producer plant which had been put down for the purposes of making gas, and not for making ash! It was decided to have a non-mechanical producer. However, during the war period they had had to take such filthy coal and found themselves making so much ash, that had they known earlier what they were going into he would certainly have tried a mechanical producer instead of a hand producer: If good fuel was forthcoming a mechanical producer was not necessary. They could, of course, transfer their cost of labour, as in other forms of firing, from the rough labour of firing to labour in their machine department, so very often they found they had machines to repair in lieu of employing hand labour. Again if they were working in a district where they could get hold of producer men with the proper 'producer sense,' they would get very good service with good or even poor coal with a hand-operated producer. The relative merits of mechanical producers and hand-operated producers depended, in his opinion, entirely on the class of fuel they were using.

Mr. COSMO JOHNS (Sheffield) said he had been very much interested in Mr. Clements' conclusions, because they were practically identical with those which would be found in a report read at an Annual Meeting some years ago. The conclusions with reference to the radiating power of carbon monoxide were, for example, exactly the same. That was extremely interesting, but he would like Mr. Clements, if he would, to tell them if his experiments and observations in any way conflicted with or confirmed the work of Professor Bone and Professor Wheeler or gave any newer information. As to the relative merits of hand-worked producers and mechanical producers, he (Mr. Cosmo Jones) had had charge of both. What did the various speakers mean by a mechanical producer or a hand-worked producer? Three things could be done mechanically: the fuel could be introduced by gravity through a bin (mechanical charging), or poking could be done by hand, or by machinery, or on the other hand a grate could be used which would discharge the ashes mechanically. To his mind the one thing that was essential as regarded efficiency was the question of the rotating hearth; that was the feature of a gas-producer which was really valuable, because it distributed the fuel in the correct way, and also served to diminish the amount of channelling and discharged the ash in the correct way.

Mr. ARTHUR H. LYMN (London) said Mr. Clements had explained what he considered should be the method of stating the calorific value of gas, and had claimed that it should be the gross or higher value, and not the net or lower value. So far as he (Mr. Lymn) knew there existed in technical industry no means of using the gross calorific value of any gas. The waste gases always escaped at a temperature higher than the condensation point, and in practice only the actual

net heat value could be used, therefore he claimed that the net value was the figure which should be stated as the value of the gas. He presumed the author gave the calorific value of the coal as the gross value. In that case likewise he thought it should be the net value.

Mr. Clements seemed to have calculated the amount of moisture which entered the producer by measuring the steam by meter, adding thereto the hygroscopic moisture and the moisture in the coal, and then deducting the condensed steam weighed. He wondered whether Mr. Clements had checked that system in any way by metering the air used, and multiplying its volume by the contained saturation steam. That would, he believed, show rather different results, and in that connection he would like to refer to the position of the saturation thermometer which was shown on the first diagram in the paper. On many occasions he himself had attempted to measure the saturation steam at a point immediately under the injector, and he had frequently found it wrong. Indeed, he had always made a point (in cases of injector blown producers) of putting an extra piece of pipe with a baffle which would ensure the steam and air mixing before reaching the thermometer. Otherwise he did not think it could possibly represent the actual figure. Mr. Clements did not state in his paper anywhere how he arrived at the volume of the gas. In his (Mr. Lymn's) opinion the only correct method would be to cool and clean the gas and measure it positively. His own opinion was that if he had done that, allowing for the sensible heat, &c., &c., the figures would have been found to be decidedly different. Then again, at a later stage, Mr. Clements took tar and soot at 10 per cent., which seemed to be rather a generous allowance. On the question of gas-producer plant generally the word "efficiency" was used very loosely indeed, and perhaps he might be allowed to refer to a suggestion which had been put forward recently at a meeting of the Institution of Mechanical Engineers, namely, that a definition should be laid down by engineers generally as to what was meant by "the efficiency of the gas-producer." Mr. Patchell was a member of the Council of that Institution, and he was one of the enthusiasts for laying down a definition, but so far as he was aware that had not yet been done. On p. 103 of the paper it was stated that, "At the higher saturation temperatures, 65° C. and 70° C., the quality of the gas was reduced, and the amount of free moisture carried was excessive." He would like to suggest to Mr. Clements that if he had increased the fuel bed still further he would not have found that result, and in that connection he might perhaps be allowed to give some particulars of the modern low temperature gas-producer process, in which a very deep fuel bed was now used—12 feet to 14 feet or even deeper. He would like to give two or three results of a three months' test with regard to that, which he thought would be found to be very interesting to the members. In that test the fuel used was of a somewhat similar kind to that used by Mr. Clements—Yorkshire fuel, namely, Bentley nuts, and the analysis of the gas averaged over the whole

time was found to be approximately as follows: CO, 9; CO₂, 21; H, 20; CH₄, 5 per cent. The gross calorific value of that was approximately 200 B.T.U. per cubic foot gross, and about 183 nett. It would be seen therefore that it was a gas which compared very favourably with any hot producer-gas, but whereas in earlier by-product practice the hydrogen replaced the carbon monoxide, it was now added thereto. He claimed therefore that the gas would be a very suitable one for use in melting steel. In the mentioned test the volume of gas obtained per ton of fuel was 118,000 cubic feet; the gas efficiency, by which he meant the calorific value of cold gas over the calorific value of the coal, was 81 per cent., excluding tar, &c. The steam decomposed was 80 per cent.; the moisture leaving the producer was 360 lbs. Mr. Clements' figure for his producer was somewhere about the same, but the actual moisture in the above-described gas after cooling was about 140 lbs. per ton of fuel. The by-products were 90 lbs. of sulphate of ammonia and about 20 gallons of tar. In general practice they would vary between 70 and 90 lbs. of sulphate of ammonia and between 15 and 25 gallons of tar. The great point to be remembered was that those by-products would reduce the nett coal bill by at least 10s. per ton, and therefore he thought those important results would be of considerable interest to the members.

Mr. J. R. GEORGE (Worcester, U.S.A.) said many of the ideas in the paper were rather new to him, and also to many other members connected with the American Iron and Steel Institute; for instance, the idea of making a survey of such a kind, which personally he thought was rather a good idea. It was a practical attempt to measure actual results. He thought it would hardly be good taste for him to criticise Mr. Clements' paper under the circumstances, and from what little he had seen of his conclusions it would probably be bad business for him to attempt to do so.

It might, however, interest those present to know that the so-called hand-charged type of gas-producer was practically unknown in the United States, and there had been none installed for, he might say, four or five years. Indeed he did not expect to see any more hand-poked producers or any hand type producers in the States. The increasing cost of coal and the shortage of labour put the hand type of producer out of the running entirely. The use of producer-gas plants in the United States was not increasing at a very great rate, nothing like in proportion to the increase in the output of steel, for the reason that they were using a mixture of tar and coke-oven gas very successfully in the open-hearth. That gave a large amount of gas for a fuel, and large quantities of oil were likewise available for open-hearth-firing, and also for heating, so that the business of gas machines was largely for replacement purposes. There had been one detailed improvement, and that was the development of a multiple type of blower which had a very high efficiency and was

practically noiseless, which was a great advantage. That blower was so very efficient that steam had to be introduced beyond the nozzle all the time in order to give moisture to prevent clinkering.

Mr. J. A. SMEETON (London) said Mr. Clements' paper was rather in the nature of an apologia for his not having gone in for modern gas-producer plant during the last few years. It was now about twelve years ago since two firms introduced mechanical producers into Great Britain, and he need hardly say that they had the same difficulty then as other firms found to-day in introducing economical modern appliances. According to Mr. Clements' paper mechanical producers had proved very lasting and efficient, and he thought anyone interested in mechanical producers, after reading Mr. Clements' paper, could only conclude that they ought not to be slow in following the lead given with regard to mechanical producers.

The experiments which had been made were very useful in showing what could be done with ideal fuel, but, unfortunately, very few works were able to work under such ideal conditions; they had to use the fuel which was placed at their disposal. When considering the installation of gas-producing plant the first thing to realise was the bulk quantity of gas required. If a large bulk of gas was required it was necessary to put into the least space at a minimum cost the necessary producer plant to give the required quantity of gas. The second thing was the quality of fuel they were going to use. If any collieries were asked for a definite continuous quantity and quality of coal they replied that it was impossible to supply such definite qualities. Of course, if a works could, by controlling their own collieries, obtain a given quantity and quality of fuel of suitable grade they would be working under ideal conditions. As a matter of fact some years ago, when he was starting up a gas-producer plant, the fuel supplied to him was such that 70 per cent. of it would go through a one-eighth mesh; it was practically nothing but dust. It also contained a very high percentage of ash, in fact as much as 40 per cent. of it came out of the ash pan at the bottom as ash and clinker. He could hardly imagine any fixed grate producer that could possibly have gasified that coal successfully, but the mechanical producer of 10 feet diameter succeeded in gasifying 25 cwts. per hour. At another battery of producers similar fuel had been supplied, and upon application being made to the works a certain grade of cobbles were supplied, and the quality of the gas produced was certainly not anything like the quality which Mr. Lynn had mentioned, in fact the analysis was 3 per cent. CO_2 , 29 per cent. CO , 11 per cent. H_7 , 3 per cent. H_4 . He always understood that a gas-producer was a generator of CO gas, and the higher the percentage of CO gas they got the better the producer was as a unit for making heat in furnaces. Probably half the trouble at producers was caused by the fact that they did not get proper attention from the man attending to them; the human element was always

present, and for that reason gas-producer designers and manufacturers had gone in for more complicated apparatus which not only did more than the human element did or could do, but which would also give the users a larger quantity of higher quality gas from a given unit more economically.

The cost of such a unit was naturally very high, but it had to be compared with the minimum space occupied, the fewer foundations and overhead bunkers, and all the other details, such as conveyers, and he thought they would find, quite contrary to Mr. Clements' finding, that a modern installation of gas machines taken from the first cost to the end would be much cheaper than a multitude of producers running along the whole row, 400 or 500 feet in length, all of which must be covered by bunkers, &c., and be fitted with gas mains, flues, and valves, to control each one to and at the desired point where the gas was required.

Therefore, taking gas-producers as generators of CO, he came to the conclusion that they could only go in for the plant which cost the least compared with the output, and he thought it was proved beyond question in Mr. Clements' paper—for which they all ought to be extremely grateful—that fixed grate producers had had their day. After all, those engaged in the production of iron and steel in England must follow the fashion to a certain extent, and, as had been stated, they were at the present time following the fashion a few years behind America, Germany, &c. Undoubtedly many works in the country had proved the superiority of mechanical plant fitted up with almost every form of improvement, and that producers of the fixed grate type were more costly and inferior in every way to the mechanical type. They had great advantages because at present they could not get the definite quality of fuel which had always been available before the war. Under those circumstances he thought it was proved once and for all for the benefit of the iron and steel trade that mechanical producers had come into their own, and that the fixed grate type was finished with and should be buried along with all the other obsolete appliances for which they had no longer any use.

Dr. W. H. HATFIELD (Sheffield) said Mr. Clements' paper was an extremely valuable one and gave a good deal of fundamental data which would form a useful basis for study by many people who were interested in the subject for a long time to come. The Institute was likewise very much indebted to the firms who had so broad-mindedly placed their data before the members of the Institute. The composition of the gas, of course, was an essential feature, and he would like to know whether the compositions were average compositions and indicative of the general results obtained from the producers of the different companies, and also in how many tests, and over what period, had that average been taken? He had been much amused at Mr. Smeeton's remarks about British practice following in the wake of foreign practice, but in comparing United States practice with, say,

that of Messrs. Steel, Peech & Tozer, it would be found that the combustibles in the American gas were something like 35 per cent., whilst gas-producers in Great Britain were getting up to 42 per cent., which meant a good deal. There was an essential feature which should not be overlooked. He did not propose to burden them with a detailed description of some experiments which were conducted two or three years ago at the works of one of their companies (Messrs. Thos. Firth & Sons, Ltd.). Mr. Clements had mentioned the distribution of temperature throughout the producer; and therefore he (Dr. Hatfield) would like to mention that in those experiments they had been successful in very satisfactorily maintaining the temperatures right throughout the bed, and they found that the gases on leaving the producer were at 600°C ., which of course compared very closely with some of the other data. They also found, however, that the maximum temperature in the producers, occurring at some 3 feet 9 inches below the surface level of the coal in their producer, was 1125°C . He thought that Mr. Clements would agree that the 1400°C . which he gave, and the figure of 1125° quoted, pointed to a variation in producer practice in relation to the maximum temperatures attained which was worthy of a good deal more study.

Mr. W. H. PATCHELL (London) said that before Mr. Clements replied to the discussion he would like to refer to Mr. Lymn's statement with regard to the efforts which had been made to get a committee together to consider producer efficiency. As a matter of fact that had been tried by the Institution of Mechanical Engineers, but it was found that there was a certain amount of luke-warmness on the part of people who were interested, so the matter was allowed to drop, in view of the fact that the Institution of Civil Engineers would shortly have the question of engine test codes under review. There was a joint committee now sitting to discuss the engine codes which had been originally drawn up by the civil engineers. The question of gas-producers formed a part of the heat engine code, and in his opinion it should be quite easy to get the committee to join in on the question of producers. He was a member of that committee, and he would be glad to mention the matter if he heard that there was any idea of participating on the part of the Iron and Steel Institute with the Institution of Civil Engineers.

Mr. F. CLEMENTS, in reply, said the paper bristled with many contentious points, but he would like to reply to Mr. Lymn's comments regarding the use of the gross calorific value of the gas instead of the net value. In his (Mr. Clements') opinion, it was scientifically unsound to take the net value, since it was an entirely arbitrary figure, and the value varied in different countries. The fact that the products of combustion were usually discharged at a temperature higher than that at which the heat in the water vapour was liberated seemed to

him no reason for ignoring it. When the calorific value of coal was determined experimentally, the gross value was obtained and, in the same way, an experimental determination of the calorific value of gas containing hydrogen gave the gross value, since in both cases the temperature of the products of combustion was reduced to the temperature of the cooling water.

He (Mr. Clements) acknowledged the difficulty of determining the volume of gas produced. He agreed that the most satisfactory way would be to meter it, but it was difficult to do that with hot gas. The values in the paper were calculated on the carbon content of the gas and of the coal, after allowing for all the losses which were measured. He agreed with Mr. Patchell and Mr. Lymn that there ought to be a definite agreed basis for calculating the efficiency of a gas-producer. The situation at present was very unsatisfactory, as there were no means of comparing the work done by one type of producer against another. With steelworks producers it was really necessary to correlate the result obtained from the producer with that obtained in the furnace, but frankly he did not see any way of connecting the two on a sound basis at the present moment. The particulars given by Mr. Lymn from the low temperature gas-producer process were decidedly interesting, although he (Mr. Clements) thought that the ordinary steel melter would experience some trouble when working with a gas containing 20 per cent. of hydrogen, although some firms had succeeded in working Siemens open-hearth furnaces with gas containing 16 per cent. of hydrogen.

He thought that the members ought to be particularly obliged to Mr. George for his comments, because his close connection with the developments of the Morgan gas machine and his intimate knowledge of American practice gave his remarks added weight. He agreed with Mr. George as to the value of an independent blower for each producer, and in that connection might refer to the remarks of Mr. Ridge and assure him that the modern tendency was to abandon the fan in favour of the steam-blower because of the better results in the producer. He would refer Mr. Ridge to Sheet No. 1, where the description of the method used to determine the moisture content of the gas was given.

In reply to Mr. Talbot he had not intended the conclusion to be drawn from his paper to be adverse to the mechanical producer. He thought that with some coals, as specified by Mr. Talbot, the only possible course was to use mechanical plant. Dealing with the same point, he would like to assure Mr. Smeeton that in his opinion there were two points of view which had to be considered with regard to the adoption of mechanical producers. The first was that of a works which had already an installation of non-mechanical producers in service and where good coal was available. It was very difficult under such circumstances to make out a case for the substitution of mechanical plant. The second consideration was that of an entirely

new works, in which case he (Mr. Clements) would without hesitation adopt mechanical producers, no matter what class of coal was available. He was not prepared to say which type of producer he would use.

He was particularly interested to learn that Dr. Hatfield had been successful in obtaining the temperatures throughout the bed of one of the producers at Messrs. T. Firth & Sons, Ltd. The difficulty which was experienced during Park Gate tests was that the iron tube which was inserted, by means of one of the poking holes, through the bed of fuel would not withstand the highly corrosive conditions existing in the hot zone of the producer. The life of one of those tubes was not more than ten minutes, and that did not give time enough to insert the pyrometer and allow it to remain sufficiently long at the various levels for equilibrium to be obtained. He (Mr. Clements) would like to re-echo Dr. Hatfield's appreciation of the way in which the co-operating firms had supplied data for the benefit of the members of the Institute.

Coming to the general question of the mechanical versus the hand-operated type of producer, he (Mr. Clements) would like to point out that the comparison arrived at in the paper was on as fair and unbiassed lines as possible. It had been suggested that he was in favour of non-mechanical producers. What he was in favour of was the best thing for the circumstances which had to be met, and he felt that, owing to the differences in the character of the coal in various parts of the country, it was necessary to make each set of circumstances the subject of a close investigation before definite action was taken on that important matter.

In conclusion he wished to say that the paper was the last of a trio, the plan of which was conceived about five years ago. Their object was to apply the methods of thermo-chemical analysis to three important sections of iron and steel works production, the blast-furnace, the Siemens furnace, and the gas-producer respectively. The purpose underlying each had been the same, namely, heat economy. From definite evidence which he had received from Italy, France, and Germany the work had been followed with close attention, but nowhere more so than in the United States of America. It was difficult to estimate whether it had had any practical effect in Great Britain, but he would like to give actual figures of what could be done. He had taken particulars from the Park Gate returns over three periods, each of sixteen consecutive weeks, as to the output of ingots and the coal used at the producers over those periods per ton of steel made. The first period was in 1919, before any revision at all had been made to their practice; the second period was in 1922, after the furnaces had been revised as far as possible along the lines demonstrated in the paper of last year, and the third period was in 1923, after the producers had been investigated and readjusted along the lines which were the subject of the present paper. The metallurgical conditions of furnace

charge and the method of operation remained the same over the three periods. The return for the coal includes all that necessary for furnace purposes, that was to say, the coal used over the week-end and also any which was required for heating up furnaces which had been rebuilt or repaired. It did not include the coal used in the metal mixer, however, which was a separate item altogether. The coal per ton of ingots was as follows :

In 1919	.	.	.	.	.	.	5.33 cwt.
In 1922	.	.	.	.	.	.	4.92 „
In 1923	.	.	.	.	.	.	4.59 „

Those results as stated were over the whole output of the shop, and if they took the data of some of the furnaces individually the results were startling. Surely it was unnecessary to emphasise the significance of the total reduction in fuel of practically three-quarters of a hundredweight, which was 14 per cent. on the original figure. That had been done consistently, and the end was not yet reached because he noticed the figure for the month of March was 4.34 cwt. He was convinced that it was along lines such as those that some measure of the future prosperity of the steel industry would lie. He thanked the members for the cordiality with which they had received his paper and for the interest displayed.

CORRESPONDENCE.

Mr. J. A. C. EDMISTON (Hamilton, N.B.) wrote that Mr. Clements' paper would be appreciated by all engaged in works practice in which producer-gas played an important part.

Dealing first with non-mechanical gas-producers, he was of the opinion that far too little attention was given to their management. It was not uncommon to find that important branch of metallurgy left to its own resources. If more scientific organisation correlated with practical experience were adopted in the management of gas-producer practice, the high efficiencies that could be obtained from the simple water bottom type would be astonishing. He considered it a most wasteful practice to have 25 per cent. carbon content in the ash. With careful manipulation of the producer a 5 per cent. carbon content could be attained without difficulty.

With regard to mechanical gas-producers, he was of the opinion that they offered no advantage over the non-mechanical type in the way of economising fuel. There would be a saving in semi-skilled labour, but he was in doubt as to the actual saving, if on the other hand skilled engineers had to be employed in making repairs. Mechanical gas-producers had their limitations as to the class of fuel that could be

used. For instance, coal could not be fed through the drum feed unless crushed to say 2-inch mesh.

He agreed that the gas should be supplied at a definite pressure. As the valves controlling the admission of the gas and air of the secondary combustion in the open-hearth furnace could not be regulated every time the gas pressure was altered, if a steady gas pressure was not consistently maintained in the gas main, there might be at such periods an excess gas in the furnace, which might do damage or go up the chimney unburned. Again, there might be an unnecessary excess of air in the furnace, carrying off heat. He held the same views as Mr. Clements, that the finely divided carbon in the gas after regeneration had an important bearing on the metallurgical value of the flame. In the regeneration of the gas, the temperature varied between 1130° and 1490° C.¹ The tarry vapours were decomposed into carbon and hydrogen at 1100° C., and naphthalene was decomposed into carbon and hydrogen at 1093° C. The tar in the gas was present as a vapour, and did not appear as a mist till the gas-tar mixture had been cooled below the tar-dew point.

He could not agree that with a 10 per cent. hydrogen content in the gas and a blast saturation temperature of 55° C. only about 50 per cent. of the steam was decomposed. In fact he had found 95 to 100 per cent. decomposition. Probably the fact had been ignored that during the gasification of washed fuel moisture could be obtained from three sources: (1) Mechanical moisture; (2) natural moisture; (3) chemical moisture. That chemical moisture was formed in the distillation of the coal in the gas-producer along with the hydrocarbons, due to a proportion of the oxygen combining with its molecular equivalent of hydrogen. Tests which he had made showed the chemical moisture to vary between 5 and 10 per cent. in different classes of fuel. If that chemical moisture had been accounted for, then approximately 100 per cent. decomposition of the steam would have been found.

The principle of the method given for determining the moisture and tar vapours in the gas was correct, but he was in doubt as to the precautions taken to ensure that only moisture was collected in the calcium chloride tubes.

Mr. B. YANESKE (Sheffield) wrote that in order to obtain rich gas concurrently with a high rate of gasification, it was necessary that the ash and fuel bed in a producer be continually or periodically poked or agitated either mechanically or by hand. The thickness of the fuel bed should be maintained as uniform as possible, non-clinkering coals being the best to use, as several hours per day were often taken up in breaking down the clinkers formed by some dusty and clinkering coals. If a uniform composition of fuel bed were maintained, there was more likelihood of the rising air and steam being brought into intimate

¹ "British Siemens Furnace Practice," *Journal of the Iron and Steel Institute*, 1922, No. I.

contact with the fuel, and no holes could be formed in the fuel bed through which the air and steam could rush without coming into contact with the coal.

Mr. Clements stated that the advantage of a 5-foot fuel bed compared with a $3\frac{1}{2}$ -foot bed was not very marked, and advocated a fuel depth of 4 feet, but it was his (Mr. Yaneske's) experience that a deeper fuel bed, say 7 or 8 feet, gave more uniform results, and there was less danger of the gases channelling through the burden. With reference to the author's figure of 1400°C . for the temperature in the producer, he considered that to be much higher than that maintained in average practice, which from his observations would be in the region of 1250°C . There could be no doubt that the gas-producers of the Park Gate Iron and Steel Co., Ltd., were worked with excellent efficiency, for their coal consumption per ton of ingots made (which was one of the chief factors upon which the efficiency of a producer could be judged) was lower than that of any other firm from which Mr. Clements obtained data. He would therefore be pleased if the author could explain why the coal consumption per ton of ingots should be as high as 12 cwts. at Messrs. Vickers' (with which firm he (Mr. Yaneske) was associated for many years), whereas at the Park Gate Iron and Steel Co., Ltd., only $4\frac{1}{4}$ cwts. of coal were used. Of course, the rapidity with which charges were worked in the open-hearth furnace had much to do with those figures, but to his knowledge the coal consumption at Messrs. Vickers', when obtaining good outputs from the furnaces, had always been very high in comparison with the coal consumption at other firms.

Considering the data given by Mr. Clements in Sheets Nos. 11, 12, and 13, for the Bethlehem Steel Company of America, as being the most suitable for comparison with Messrs. Vickers' practice, it would be observed that the former company used two gas-producers for a 75-ton furnace to Messrs. Vickers' one for a 30-ton furnace, the producers being of similar gasifying capacity. While the quality of gas obtained by the Bethlehem Steel Co. was inferior to that of Messrs. Vickers', both in combustibles and calorific value, it was remarkable that the coal consumption per ton of ingots made was only 5 cwts. at the works of the Bethlehem Company against 12 cwts. at Messrs. Vickers'. He was much interested in that comparison, and would be pleased if Mr. Clements could put forward a satisfactory explanation for the existence of such a vast difference in the amount of coal consumed by the respective firms.

In reply to the discussion by correspondence Mr. CLEMENTS wrote that he was obliged to Mr. Edmiston for calling attention to the need for better management of non-mechanical gas-producers. There was no other branch of metallurgical equipment which more readily responded to proper treatment than the gas-producer, and he was convinced that much money was lost by the inattention which was

usually displayed. With careful manipulation, such as was within the capacity of any ordinary gas-producer attendant to give if he understood his work, the result obtainable from non-mechanical producers was equal to that obtainable from mechanical plants, given favourable conditions regarding the quality of the coal. The chief feature, however, which made mechanical plants attractive was the elimination of that need for close supervision, and on this ground alone he (Mr. Clements) was of the opinion that the mechanical producers would eventually prevail.

The question of the moisture decomposition was a difficult one to deal with, but he thought that if the chemical balance-sheet was carefully worked out for any given set of conditions, then the figures given in the paper would be found to be accurate.

In reply to Mr. Yaneske, Mr. Clements stated that the manipulation of clinkering coals was one of the main difficulties of the mechanical producer. A properly designed producer should eliminate any trouble from this cause, but such was not the case in all mechanical units. If hand-poking had to be resorted to, then the advantage claimed for the mechanical type was largely lost. However, some of the designs were certainly successful in dealing with coals of that nature, and he would like to say that trouble sometimes arose through no fault of the design of the producer but through its incorrect manipulation. It was as necessary correctly to adjust the conditions within the mechanical type of producers as it was in one of the non-mechanical type. With regard to the temperature in the hot zone of a producer, he would be inclined to the opinion that a temperature of 1250° C. in that region indicated that the producer was being oversteamed, and more efficient results would follow a reduction in the quantity of steam and an increase in the hot zone temperature. He would like to point out the importance of economy in the use of steam because of the large amount used which, if not decomposed, represented almost entirely a direct loss of heat.

Iron and Steel Institute.

ON SOME CHARACTERISTICS OF MOULDING SANDS AND THEIR GRAPHICAL REPRESENTATION.

By J. E. FLETCHER (DUDLEY).

IN the early days of moulding-sand research the author, with the help of his friend, Mr. Harry Brearley, employed subsidence tests to determine the mechanical and chemical characteristics of the sands and compositions employed at that time for steel-casting moulds. By shaking together definite quantities of water and sand in a standard test-tube or graduated jar and allowing the sand, silt, and clay to settle, the depths of the various strata were more or less clearly defined and, with the additional help of sieving, an index to the mechanical grading of the mixture was afforded. Chemical analysis of the separated grades gave further information of very helpful character, and the method was used for years by the author before any published data on sand research was available.

More recently the very valuable researches of Professor Boswell here, and Messrs. Hanley, Simonds, Doty, Hall, Schwartz, and others in the United States, have enabled foundrymen to attack the moulding-sand problem with more scientific precision. Particularly in the matter of the determination of the size of the grains in the various grades constituting a moulding sand has the substitution of elutriation for subsidence methods of mechanical analysis proved valuable. The desirability, however, of some simpler and more direct method to indicate the characteristics of a moulding sand has been very generally recognised.

The present paper is a description of an attempt to indicate some of the important characteristics of moulding sands by means of a simple subsidence method, based on the author's earlier experiments, already alluded to.

THE METHOD.

For general handiness and practicability, test-tubes of 35 millimetres ($1\frac{1}{3}$ inch) internal diameter and 230 millimetres (9 inches) long have been employed.

The sand to be examined is slowly dried and passed through a 30-mesh sieve, fed into the test-tube slowly through a funnel, and gently shaken to a level of 3 inches above the bottom of the tube. Tap water, cooled to 15° C. after boiling, is poured into the tube, covering the sand by a depth of 4 inches. The water and sand are then vigorously shaken by hand—a method found more effective than mechanical stirring or whirling, and yielding more regular results. After shaking, the sand is allowed to settle in the vertical tube for, say, five minutes, when the water level will be found to have subsided by a definite amount, the new level remaining constant. The volume represented by the fall in the water level is a measure of the voids between the sand, silt, and clay grains, and furnishes an index of the type and openness of the grain packing, and also, approximately, of the gas permeability of the sand.

The tube is next filled to the brim with water at 15° C. and shaken as before until, by a similar indication, mixture is effected. At the moment of complete mixture of the water and sand the tube is held vertically, and the time taken for the fall of the sand grades (C.S., M.S., and F.S.), the level of which rises until the sedimentation of these grades is complete, is noted. The moment chosen for the upending of the tube and its contents is the time taken as the commencement of the test, and the time taken for the subsidence of the sand grades affords a measure of the mean size of the grains in these grades. With some sands it is possible to time the sedimentation of two or three distinct grain sizes in this first subsidence.¹

The tube is next placed to rest in a truly vertical position, and the level of the silt and clay subsidence noted every one or two minutes for one hour, and, later, every ten minutes, until a stable level has been reached. As the silt and clay subside, the

¹ A curve plotted upwards and to the left of point O in Fig. 1 (as curve *opqrs* in Fig. 4), using the abscissæ scale as *seconds* instead of minutes, is generally practicable, and adds to the value of the diagrams. This curve will clearly indicate the grain sizes in the M.S. and F.S. grades, and will define the relative bulk percentages of the grades.

level of demarcation between the more or less clear water and the underlying mixture (silt + clay + water) is clearly defined.

THE SUBSIDENCE DIAGRAM.

On plotting the results on a time base, a curve characteristic of the moulding sand under test is obtained.

Fig. 1 gives the subsidence curve of a Belgian yellow moulding sand of similar chemical and mechanical analysis to that cited by Professor Boswell in his "Memoir on Sands," Part I., p. 62. Mean chemical analyses of the sand and clay grades gave almost exactly similar values to those of Professor Boswell, and in the case of other sands examined, the grade analyses of Wolverhampton, Kingswinford, French red, Cornish red, and Mansfield were very closely similar to those given in the Memoir referred to.

Such being the case, the comparison of the author's curves with the curves of cumulative percentages of the various grades as prepared by Professor Boswell is interesting and practically useful. Whilst the latter show the percentage weight of each grade, the former illustrate in a striking manner the mechanism of the progressive subsidence of the silt and clay grades.

A closer examination of the subsidence curve in Fig. 1 brings out the clear differences in the two grades of silt and the characteristics of the clay grade. The effect of the silt grade in moulding sands has long been recognised as being of vital importance; the lower the percentage of silt the better, and where present in quantity, the more uniform the size of the silt grain the more permeable the sand. A like condition in the clay grade is desirable.

Uniform size of the sand-grade grains is, of course, of primary importance, but as the gas permeability of a moulding sand is controlled by the type of grain packing, the effect of the silt grade, which so often mars the efficiency of an otherwise good sand, is well worthy of study. The author's curves indicate the mode of occurrence of the silt grade, and Fig. 2 has been prepared as indicating the three types of silt effect.

Curve A illustrates the presence of silts and clays of progressively diminishing grain size. It is somewhat difficult to say where the silt grade ends and the clay grade begins. Such

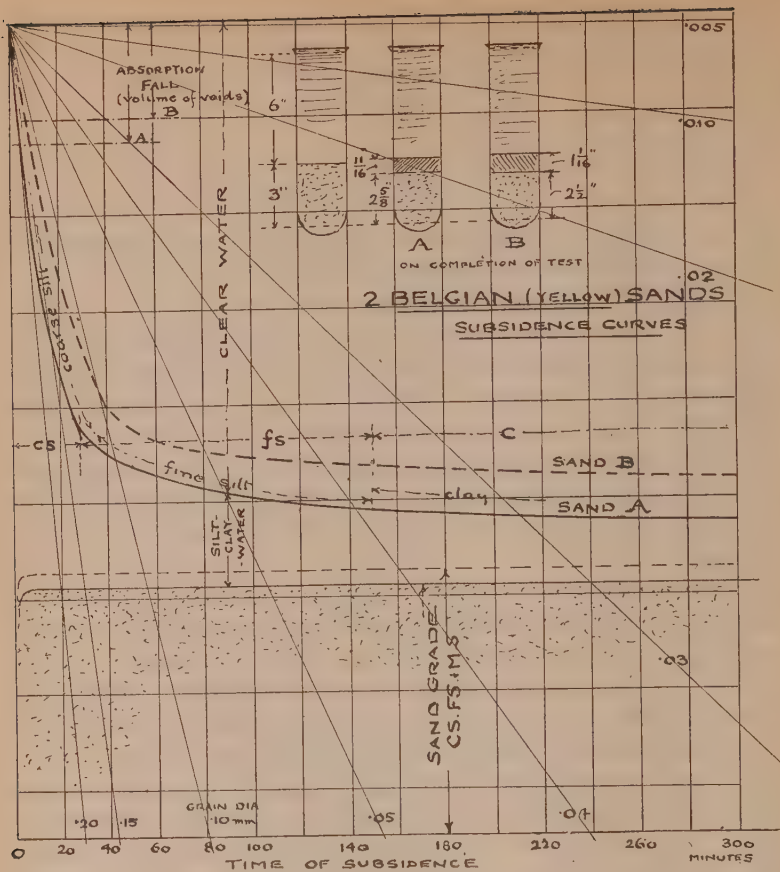


FIG. 1.

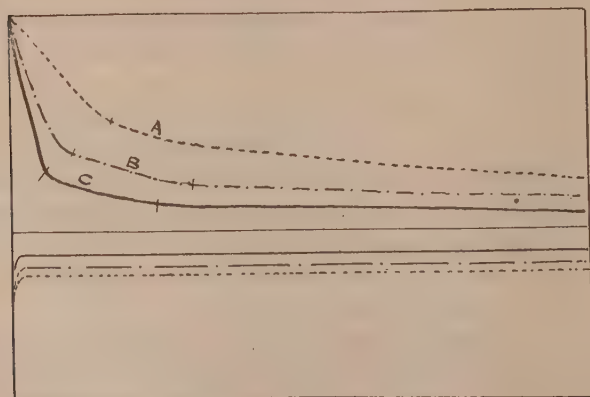


FIG. 2.

conditions militate against good gas permeability, although the sand may possess excellent bonding strength. The curve is characteristic of several well-known sands rich in alkaline content. The silt grains are of small diameter.

Curve B shows two distinct types of silt grade, one of medium size, the other of fine texture. When this is noticed the clay grades are often present in two grades, differing in grain size.

Curve C is representative of some of the best moulding sands, there being only a small percentage of silt which, as in curve B, is divided into two distinct grades, each grade being of uniform grain size (the straight line portions being always indicative of uniform velocity of grain subsidence, and hence of grain size). The clay grade sedimentation is regular, almost a straight line throughout its length, indicating uniformity of grain size.

POROSITY AND GAS PERMEABILITY.

In a study of the grain pack, as H. A. Schwartz has shown, it is exceedingly difficult and unsafe to dogmatise on the relative volume of the voids in the sand-grade portion; but it is useful to remember that in the open, intermediate, and closest types of spherical packing, with spheres of equal size, the voids occupy approximately 47, 40, and 26 per cent. of the total.

It has already been stated that, in the author's subsidence tests, the amount of water absorbed by the sand during the first shaking up of the dry sand and water gives a clue to the percentage of void volume. This absorption volume varies, in the sands tested, from 30 to 40 per cent., approximately. It should be noted, however, that when the coarser sand grains are settling down and the air (churned up in the shaking) is escaping, the silt and clay particles are displaced and driven upwards by air and water currents. The absorption volume indicated by the drop in the water level is therefore a measure of the voids between the sand grains washed more or less clear from the silt and clay. When, after the second shaking, the sand, silt, and clay again subside in the absence of air, each sand or silt grain is wetted, and the velocity of fall is, proportionally, nearly in accord with Stokes's law for grains under, say, 0.10 millimetre diameter (*i.e.* directly as the square of the grain diameter), although more

nearly agreeing with Boswell's corrected values, as ascertained from elutriation experiments. It is likely that the size of the tube used (35 millimetres diameter) is smaller than that theoretically necessary for the unimpeded fall of the grains, but the trial of larger tubes did not appear to give superior results, and was not so handy.

VELOCITY OF GRAIN DESCENT.

Reverting to the subsidence curves, it will be seen that three generally distinct angles of slope occur, each corresponding with the velocity of fall of three different grain-size grades.

In the earlier stages of the experiments, the effect of varying heads of water above the sand level was noted. The variations in the curves obtained when 2, 3, 4, 5, and 6 inches respectively were added above a 3-inch sand layer are seen in Fig. 3. The sand tested was from the Belfast area and contained a high percentage of fine silt. The curves are steeper as the water head is increased.

It is clear that the amount of air churned up with the water before sedimenting (in this case the curves were taken immediately after the first shaking) has an effect on the rate of grain descent, the ascending air bubbles opposing the fall. The larger the volume of air in the mixture, the slower the grain-fall velocity. It is easy to observe in such tests the ballooning effect in carrying up with the air bubbles particles of fine silt and clay.

By filling up the tubes after the first shaking, and again allowing the sand to subside after a second agitation, regular results were obtained, the five curves being alike. It was, however, observed that in repeating the experiment with 2, 3, 4, 5, and 6 inches of water head, the tubes being stoppered down to the water level so as to exclude air, the slopes of the silt grade subsidence varied, as in the first case, though not so markedly. One explanation of this variation in silt grain fall velocity would appear to be the coating of the silt grains by a clay film, thereby increasing the grain size and speeding up its velocity of fall. The deeper the fall, the greater the thickness of the clay film.

In foundry practice the addition of a fine fireclay to "used" sand in a well-wetted mixture brings about a similar grain growth,

but here the great practical difficulty in obtaining homogeneous and uniform results is obvious. The author has noticed, in this connection, the rapid deterioration of synthetic sands made by mixing highly silicious sands with fireclays, when these have been allowed to lie unprotected from the weather. A few heavy

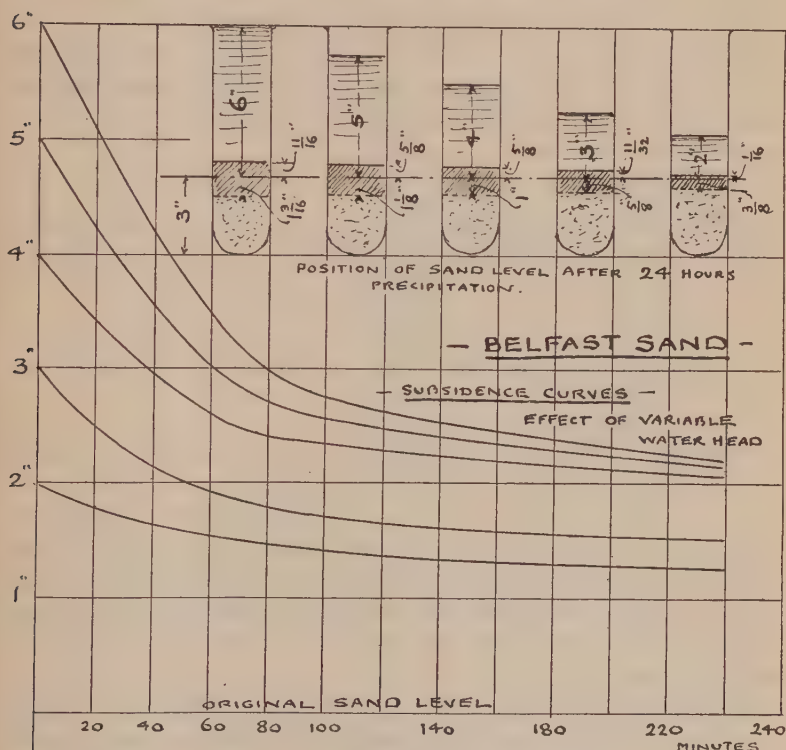


FIG. 3.

rain-storms will soon ruin such a heap of sand. The "burning-on" troubles resulting from such an experience are not soon forgotten by the foundryman who has been unwise enough to use such sand without remilling and effective mixing.

In elutriation methods there is a possibility, when using water currents of excessive velocity, of reducing the grain size of sand covered lightly by the clay film. In some cases very misleading results have occurred. The author has noticed this scouring

effect when sedimenting sands which have been repeatedly shaken.

COMPARISON OF THEORETICAL AND ACTUAL SUBSIDENCE DIAGRAMS.

As already stated, the subsidence curves at once give an index to the grain size. They also indicate the relative volumes of the various grades. The construction of a subsidence diagram from known data may throw light on the elucidation of the actual graphs presented.

A moulding sand may be taken as an example, having the following mechanical composition :

(a) Medium and fine sand grade (M.S. and F.S.)	80 per cent.
Average grain size, 0.25 millimetre.	
Subsidence velocity per second, 25 millimetres.	
(b) Coarse silt grade (c.s.)	4 „
Average grain size, 0.10 millimetre.	
Subsidence velocity, 6.7 millimetres per second.	
(c) Fine silt grade (f.s.)	6 „
Average grain size, 0.025 millimetre.	
Subsidence velocity, 2.5 millimetres per second.	
(d) Clay grade (c.)	10 „
Average grain size, 0.007 millimetre.	
Subsidence velocity, 0.05 millimetre per second.	

In Fig. 4, the water and sand being thoroughly shaken together, the various grains are assumed to be uniformly distributed within the water mass. Also velocities are assumed to be constant throughout the grain-fall period in the case of each grain grade.

In A, B, C, and D the lines xp , xq , xr , and xs give the slopes corresponding with the velocities of the grains in each grade. At the end of the descent of each grade the upper surface of the sedimented matter is shown at levels p , q , r , and s , and in D the progressive curve of the subsidence is given— $Pqrs$ —on the assumption that each grade is sedimented separately without admixture of any other grade. By estimating the voids in each grade as 40 per cent. of the total grade volume, it is possible to trace the progress of the subsidence at the completion of the sedimenting of the various grades. The free water above the already sedimented grades can be estimated, and the ratio R of free water to depth of sediment arrived at. The curve of these

ratios, starting from the end of the clay grade, marked *s*, *m*, *l*, *x*, will be found to approximate to the subsidence curve obtained by actual observation.¹

In some cases, as in that of Belgian type sands of high clay grade content, the velocity curve of the coarse silt grade suggests a higher grain velocity than the silt grain size, as determined by elutriation methods, would demand. Here there appears to

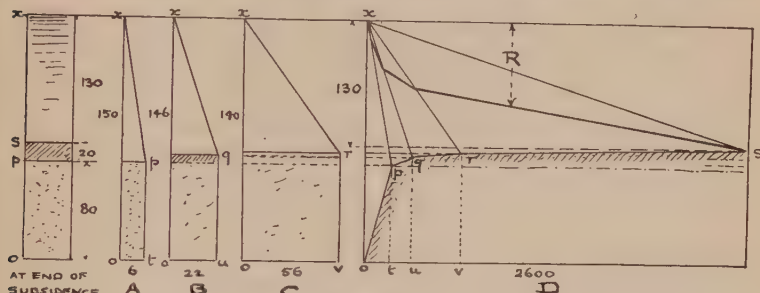


FIG. 4.

be a growth of grain during subsidence, due to the clay filming action before described.

In Fig. 5 the subsidence curve of a Bunter moulding sand from Kingswinford, Stourbridge, is shown, the curve corresponding with the estimated values of *R* being added at *K*. On this diagram three other curves are illustrated from tests made on French red, Mansfield, and Belgian yellow. The oblique lines traversing the diagram correspond with the velocity slopes representative of the grain fall of sand, silt, or clay grains of the diameters marked. By comparing the slope of the various grades in the sands thus graphed with these oblique velocity lines, it is easy to arrive at the approximate size of grains in any grade.

LAG IN GRAIN-FALL VELOCITY.

In the subsidence curves described it must be noted that the "grain-fall-time" curve never coincides with the theoretical curve plotted for the progressive subsidence of the various grades

¹ A comparison of the curve *pgrs* with Professor Boswell's cumulative curve for the sand is of interest.

TABLE I.—*Subsidence Data, as estimated from Tests of Seven Typical Moulding Sands A, B, C, D, E, F, and G (see Table II.).*

	A.	B.	C.	D.	E.	F.	G.
Total M.S., F.S., c.s., f.s., and c. grades sedimented at end of M.S., F.S. subsidence	Mm. 64.51	Mm. 58.52	Mm. 68.44	Mm. 63.64	Mm. 58.63	Mm. 65.15	Mm. 52.87
C.s., f.s., and c. in suspension at end of M.S., F.S. subsidence	<div> <div>c.s.</div> <div>f.s.</div> <div>c.</div> </div> <div> 0.82 1.30 2.45 </div>	<div> <div>c.s.</div> <div>f.s.</div> <div>c.</div> </div> <div> 1.61 5.15 6.00 </div>	<div> <div>c.s.</div> <div>f.s.</div> <div>c.</div> </div> <div> 0.81 0.86 5.25 </div>	<div> <div>c.s.</div> <div>f.s.</div> <div>c.</div> </div> <div> 1.01 1.52 7.30 </div>	<div> <div>c.s.</div> <div>f.s.</div> <div>c.</div> </div> <div> 4.00 1.28 6.92 </div>	<div> <div>c.s.</div> <div>f.s.</div> <div>c.</div> </div> <div> 1.81 1.67 4.32 </div>	<div> <div>c.s.</div> <div>f.s.</div> <div>c.</div> </div> <div> 9.42 3.38 2.87 </div>
Water of suspension . . .	165.50	171.50	161.60	166.40	171.40	164.90	177.10
Ratio $R = \frac{\text{water volume}}{\text{c.s.} + \text{f.s.} + \text{c. vol.}}$	36.7	21.3	23.3	17.0	14.0	21.1	11.2
Total M.S., F.S., c.s., f.s., and c. grades sedimented at end of c.s. subsidence	Mm. 65.18	Mm. 66.68	Mm. 68.73	Mm. 66.96	Mm. 67.66	Mm. 71.07	Mm. 72.01
f.s. and c. in suspension at end of c.s. subsidence	<div> <div>f.s.</div> <div>c.</div> </div> <div> 0.53 2.36 </div>	<div> <div>f.s.</div> <div>c.</div> </div> <div> 1.95 5.90 </div>	<div> <div>f.s.</div> <div>c.</div> </div> <div> 0.35 5.20 </div>	<div> <div>f.s.</div> <div>c.</div> </div> <div> 0.60 7.22 </div>	<div> <div>f.s.</div> <div>c.</div> </div> <div> 0.54 6.90 </div>	<div> <div>f.s.</div> <div>c.</div> </div> <div> 1.16 4.27 </div>	<div> <div>f.s.</div> <div>c.</div> </div> <div> 1.35 2.82 </div>
Water of suspension . . .	164.80	161.30	161.30	163.00	162.20	158.80	157.00
$R = \frac{\text{water volume}}{\text{f.s.} + \text{c. volume}}$	57.0	20.5	29.0	21.3	22.0	29.5	37.3
Total M.S., F.S., c.s., f.s., and c. grades sedimented at end of f.s. subsidence	Mm. 68.09	Mm. 70.02	Mm. 71.39	Mm. 68.03	Mm. 68.64	Mm. 72.95	Mm. 74.29
Clay grade c. in suspension at end of f.s. subsidence	2.34	5.90	5.17	7.18	6.80	4.22	2.82
Water of suspension . . .	161.90	160.00	158.60	162.00	151.60	157.00	155.70
$R = \frac{\text{water volume}}{\text{c. volume}}$	68.5	27.2	30.8	22.6	22.2	37.0	55.1

Note.—The position of the upper level of the c. + s. in suspension—the subsidence curve being the loci of such progressive positions—is clearly determined by the relative proportion of silt to clay in the water of suspension. The higher the silt proportion, the lower the curve. In sands B, C, D, and E, the clouded character of the water of suspension during subsidence was marked, especially in sands D and E, where the ratio R, 22.6 and 22.2, was lowest. The high percentage of colloidal clay in suspension apparently increases the virtual viscosity of the water and reduces the velocity of grain fall. This has been confirmed by many later tests, and clearly shows that the pressure of clay concentration directly retards the silt grain rate of subsidence.

TABLE II.—*Mechanical and Chemical Analyses of Seven Typical Moulding Sands Tested.*A, B, and C, Belgian. D, French red. E, Mansfield. F, Kingswinford.
G, Belfast.

M.S. F.S.	c.s.	f.s.	c.	SiO ₂ .	Al ₂ O ₃ .	FeO, Fe ₂ O ₃ .	CaO, MgO.	TiO ₂ .	Na ₂ O, K ₂ O.	H ₂ O, CO ₂ .	Sand.
79.1	2.3	3.0		96.7	1.09	0.69	0.32	0.11	0.40	0.88	
				75.6	9.80	5.80	1.38	0.95	1.20	5.80	A
			15.6	45.6	22.20	11.90	3.10	1.24	1.94	14.00	
71.2	4.1	12.10		95.7	1.15	0.73	0.41	0.16	0.39	1.40	
				66.7	11.20	8.10	0.52	0.83	1.46	11.10	B
			12.6	43.1	23.30	12.80	2.74	1.36	1.78	14.90	
85.6	1.5	2.0		96.8	0.95	0.70	0.26	0.15	0.47	0.71	
				77.2	8.92	4.70	1.10	1.12	0.96	6.00	C
			11.9	43.4	23.6	10.50	2.93	1.32	1.82	16.20	
77.7	2.3	3.5		96.3	1.03	0.50	0.41	0.14	0.46	0.65	
				55.4	19.10	10.12	2.08	0.91	2.12	10.20	D
			16.5	45.7	21.16	13.35	3.62	1.05	2.61	12.60	
71.5	10.3	3.0		86.2	6.30	1.31	1.42	0.18	1.42	3.20	
				73.5	7.12	1.36	5.16	0.72	5.05	7.00	E
			15.2	39.6	20.21	3.40	15.73	0.96	5.14	15.20	
80.4	4.5	6.6		92.2	4.02	0.61	0.42	0.18	2.32	0.32	
				79.3	8.11	2.36	1.15	0.72	4.05	4.20	F
			8.5	58.1	19.60	6.10	3.11	0.82	5.42	6.80	
62.3	23.6	8.5		85.6	6.30	0.65	0.55	0.18	1.82	4.70	
				70.3	8.75	1.78	3.67	0.39	3.98	11.20	G
			5.6	41.8	21.53	3.82	4.53	0.91	5.64	12.20	

composing a moulding sand, the sizes of the grains in each grade being known. The fact is, that whilst the C.S., M.S., and F.S. grades are subsiding the silts and clay are simultaneously falling, each grade descending at a velocity corresponding with the grain size, so long as there is no opposing influence. This condition is only fulfilled when the grains fall separately in an excess of water in a tube or tank of large dimensions.

In the tests described the mean sand and water volumes at the moment of the second shaking are approximately in the ratio

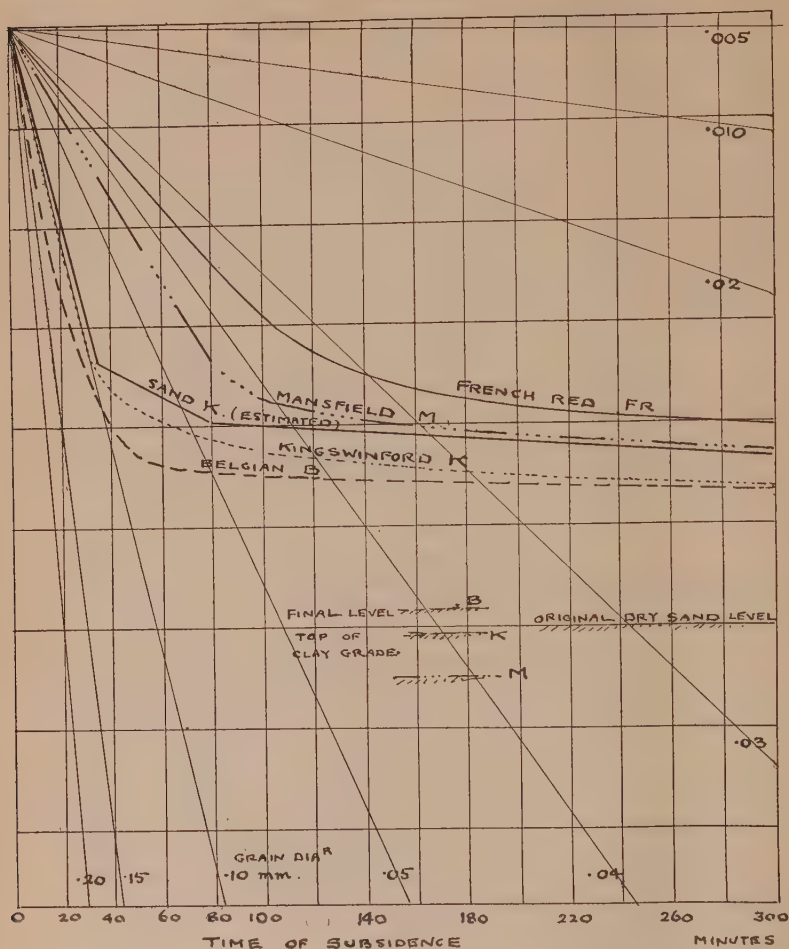


FIG. 5.

1 to 4—that is, each cubic millimetre of sand may be considered as surrounded by 4 cubic millimetres of water. More particularly, taking the case of a moulding sand consisting of 80 per cent. M.S., F.S. grade, 5 per cent. each c.s. and f.s. grades, and 10 per cent. clay grade, of grain sizes 0.1, 0.05, 0.01, and 0.005 milli-

metre diameter respectively, the number of grains in the respective grades per unit volume will be 1, 8, 1000, and 8000. The volume of each grain in each grade being taken as unity, the water volume as apportioned to each such grain will be found to be 1, 4, 5, and 10 in the M.S., F.S., c.s., f.s., and c. grades respectively, and the thickness of the water envelope surrounding each grain of unit dimension will be 0.13, 0.355, 0.408, and 0.612 respectively.

The interference to fall (the velocity of descent being taken as proportional to the cross-sectional area of the grain) will probably be a function of the order—

$$\frac{\text{Area of falling grain cross-section}}{\text{Area of water envelope cross-section}}$$

or, in the case cited, as 0.63, 0.34, 0.30, and 0.20 respectively. This interference is analogous to the fall of a large grain through a small tube, or to that of a small grain through a large tube.

The descent of a grain of unit cross-sectional area through a tube of cross-sectional area 1.587, as representing the case of the M.S., F.S. grains, at a velocity of 6.7 millimetres per second, displaces the water which escapes upwards past the grain at a velocity of $\frac{6.7}{0.587}$, or 11.4 millimetres per second (ignoring frictional or inertia losses). Similarly, in the other grades :

In c.s. grade, grain-fall velocity 1.78 millimetre per second. Counter water current velocity is 0.93 millimetre per second.

In f.s. grade, grain-fall velocity 0.12 millimetre per second. Counter water current velocity is 0.05 millimetre per second.

In clay (c.) grade, grain-fall velocity 0.087 millimetre per second. Counter water current velocity is 0.022 millimetre per second.

The ascending water currents thus set up by the grain fall are sufficient to prevent the descent of, and indeed to carry up with them, grains of relatively large size. This is actually observable during the subsidence of the M.S., F.S., and c.s. grades. The small grains are carried upwards until their velocity falls to nil, when they recommence their descent. In some cases the clay particles have been observed to ascend almost to the top of the water column, a distance of, say, 200 millimetres, before coming to a standstill and redescending.

It is plainly the silt and clay grades which are mainly affected

by this water contra-flow action, and the author has concluded that the lag in the subsidence curves—in the silt grade portions particularly—is due to this action. The lag being thus proportional to the grain size and grade percentage and to the clay content particularly in a moulding sand, the curve is characteristic of the sand composition.

It should be possible to correlate the experimental curves with the contra-flow velocities of the water of suspension as calculated from known values of grain size, and to their already ascertained grain-fall velocities. A series of curves should result which, by comparison with actual subsidence curves, would help to standardise the graphs for typical sands, and similarly for other detrital or disintegrated materials.

The lag above referred to has been noted in the preparation of the subsidence curves illustrated, and by correlating the coarse silt slope (in a sand having a grain size (c.s.) of approximately 0.1 millimetre) with that of similar grains falling freely at the rate of 1.78 millimetre per second, the oblique lines have been drawn for the various grain sizes. The slope of the curve representing the coarse silt subsidence was taken as corresponding to Stokes's law velocity for 0.1 millimetre grains and the oblique line marked 0.1 drawn through it, the remaining lines being drawn in positions relative to the velocities given by Professor Boswell for the other grain sizes.

THE EXAMINATION OF "USED" SANDS.¹

The author has found the method useful in examining the nature of "used" sands, and of mixtures of new with "used" sands. Such a comparison is shown in Fig. 6. Here the sands examined were from a foundry using moulding sands from the Stourbridge area exclusively. The effect of mixing used floor sand with various proportions of new sand is seen in the diagram. The absorption drop in the water level after the first shaking of the dry sand and water varied in each case, and emphasises the point recently described by H. A. Schwartz in a paper read before

¹ There is much to suggest that the contour of the curves is primarily influenced by the clay concentration in the water of suspension. Experiments on moulding sands and fireclays so far support the view that the rate of silt and sand subsidence varies directly as the clay content in the water of suspension.

the American Foundrymen's Association. He showed that when mixing coarse and fine sands together in all proportions there

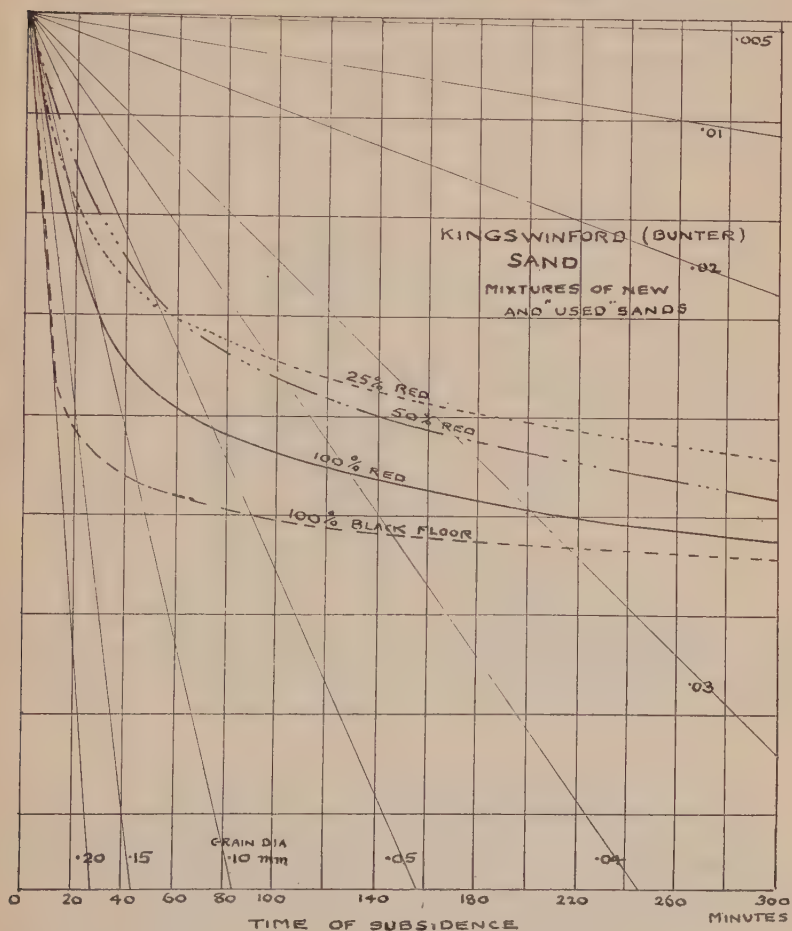


Fig. 6.

is a mixture possessing the minimum of gas permeability. The results of the author's tests on the absorption values of mixtures of new and used Stourbridge sands are shown in Fig. 7.

The important effect resulting from the growth of grain by the "clay-filming" of "used" sand grains is clearly shown in

Fig. 6, the velocity lines of the various mixtures being significant. The silt grade slopes are steeper in the case of the mixtures rich in "used" sand than in the case of the new red sand. The

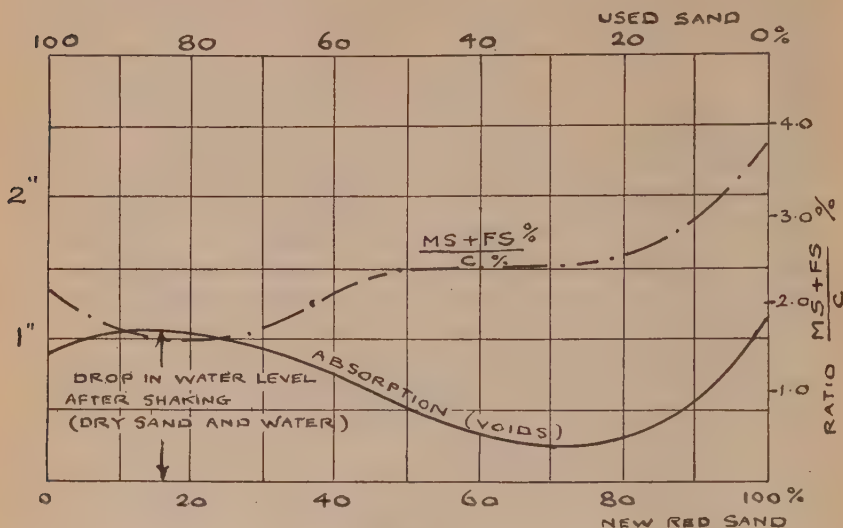


FIG. 7.

absence of the straight-lined profile of the mixture containing 25 per cent. red and 75 per cent. black used floor sand is especially noticeable, denoting a mixture of many sizes of grain in the silt grade and explaining the poor gas permeability.

THE MINERALOGICAL COMPOSITION OF SANDS.

Much remains to be done in the mineralogical analysis of moulding sands, and any real understanding of the bonding characteristics of a sand must be sought in the determination of the actual constitution of the silicious grain, which is the nucleus around which the bonding materials, ferric and argillaceous, are more or less statically wrapped, as suggested by Mr. C. W. H. Holmes in his recent paper.

The interpretation of the chemical analysis of a grade in terms of the mineral rock minerals, in their primary or altered conditions, is therefore of the utmost value. It is important to know whether the free silica in a sand grain is firmly attached

to its felspathic neighbour, or whether as a slippery-faced crystal it is incapable of properly bonding with the limonite or kaolinite in its immediate vicinity. In conjunction with the study of the subsidence curves it is essential, therefore, that the mineralogical constitution of each grain grade should be determined. Fig. 8 gives an approximate outline of the mineralogical composition of the various grain grades of naturally bonded moulding sands,

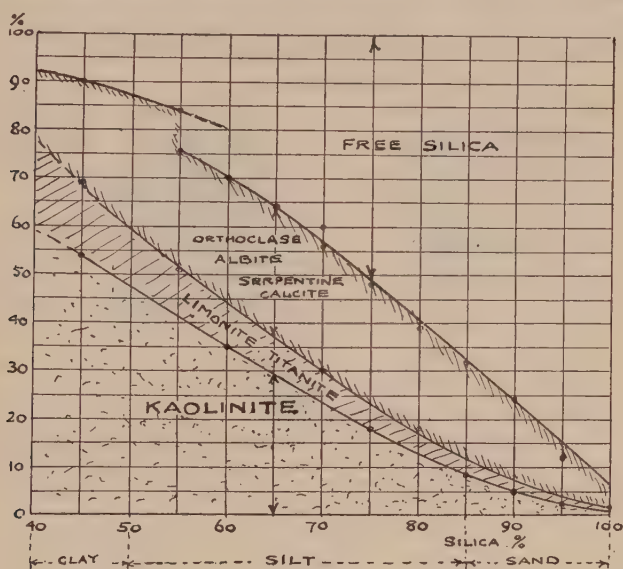


FIG. 8.

and is added with a view to drawing attention to this section of moulding-sand research. It is extremely interesting to observe the continuous connection between the various grades: the diminishing proportion of free silica and the increasing proportion of the bonding materials, limonite and kaolinite, as the clay grade is approached; the decrease of felspathic minerals in the sand grade and the uncertain composition of the clay grade.¹

¹ By carefully "panning" a sand sample, the heavy minerals magnetite, ilmenite, rutile, garnet, zircon, anatase, staurolite, hæmatite, &c., can be separated sufficiently in a few repeat samples to indicate, when examined under the microscope, the relative quantitative content of such heavy minerals in the sands under test. The presence or rarity of certain minerals in defined strata of Bunter sands, for example, is an index to the bed from which the sand has been taken, and may, when correlated with the moulding characteristics of such sand, be of practical and commercial value.

In the development of synthetically made or mixed moulding sands, and in the scientific preparation of moulding sands, it is hoped that the suggested line of study indicated in the paper will be of use to foundrymen. The author's methods are admittedly in the nature of works determinations and will undoubtedly be improved upon. They have already proved of some considerable practical value, and have been used in giving

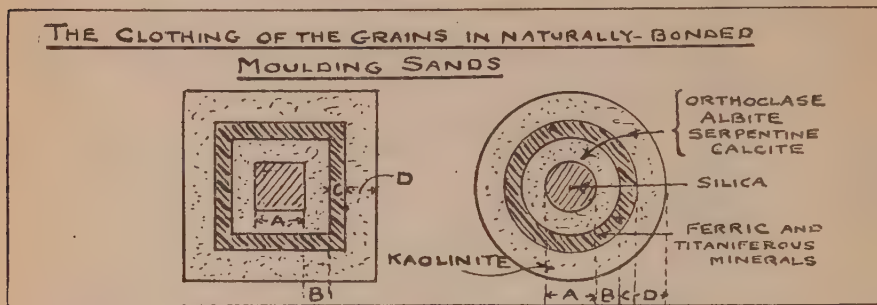


FIG. 9.

TABLE III. (See Fig. 9.)

GRAIN SIZE	Mm. 0.10 to 0.25.	Mm. 0.05 to 0.10.	Mm. 0.01 to 0.05.	Mm. below 0.01.
	F.S.	c.s.	f.s.	c.
NUCLEI				
Size of Silica Nucleus A .	1.00	1.00	1.00	1.00
Thickness of Feldspathic Jacket B	0.006 to 0.045	0.02 to 0.06	0.06 to 0.18	0.17 to 0.26
BOND				
Thickness of Ferric and Titaniferous Jacket C	0.001 to 0.003	0.005 to 0.025	0.01 to 0.04	0.020 to 0.080
Thickness of Kaolinitic Jacket D	0.003 to 0.010	0.015 to 0.060	0.04 to 0.16	0.140 to 0.300
Density of Minerals (S.G.)	A 2.60	B 2.55	C 3.60	D 2.25

The above relative values have been computed from the samples of sands outlined in Fig. 8, on the hypothesis that the free silica (quartz, &c.) grains A are concentrically covered by the mineral constituents B, C, and D.

advice to a number of the members of the Cast Iron Research Association.

In conclusion, the author wishes to express his gratitude to several foundry friends, who have furnished samples of sands for examination, and in particular to Mr. F. J. Cook of West Bromwich, to Mr. W. B. Parker of Rugby, for their advice and help, and to Mr. S. J. Astbury of Messrs. N. Hingley & Sons, Netherton Ironworks, for his help in the analyses of sand samples.

CORRESPONDENCE.

Mr. C. W. H. HOLMES (Birtley) wrote that he had obtained tubes of the same dimensions as those described in Mr. Fletcher's paper, and had repeated some of his (Mr. Holmes) own experiments—made in smaller tubes and discontinued some time ago—as well as such other tests as time permitted. He did not think that a 12-mesh sieve was fine enough, especially when testing Erith or similar loams. Instead of adding 4 inches of water (p. 140), why not calibrate the tube and add a standard volume of water from a measuring cylinder? That tended to remove the variation caused by bubbles of air being liberated from the sand before all the water had been added. That method of measuring the approximate voids in the sand tended to make a sand of low permeability appear better than it actually was.

He wished to ask what the units on the vertical ordinate in Fig. 1 were, and to have details as to how the 25 per cent. and 50 per cent. Kingswinford mixtures were made. Were they milled together, or simply mixed? The data in Fig. 7 did not confirm that in Fig. 6, neither did it agree with the statement (p. 154) in which the 25 per cent. red, 75 per cent. black sand mixture was described as being the least permeable. Fig. 7 showed that mixture as approaching the maximum permeability. He was inclined to think from his own experiments that more interesting results were obtained when only half the quantity of sand was used; or, preferably, the same quantity of sand in a tube twice as long. That applied more to the early stages of sedimentation, and especially with high clay contents. With such sands as South Cave, Belgian, Erithstrong, and Mansfield, the clay concentration became too high for optimum sedimentation conditions to obtain.

The use of tap water raised a question of great interest, in that it varied widely from one district to another, and the various salts in solution had some influence on the coagulation of the colloidal bond, and hence on the rate of sedimentation. He had been carrying out experiments recently, using $1/10^3$ molar solutions of various salts, with a view to obtaining some information regarding the nature of the colloids in the bond. The matter was complicated by the fact that distilled water after contact with a sand—for example, Mansfield—contained SO_4 , Cl, Na, Ca, and Mg ions in solution.

Evidently the salts adsorbed by the colloidal matter were taken up to some extent by the water until equilibrium was attained. The result was that Mansfield, and other sands, would coagulate in distilled water. He found that the upper margin of the clay and silt subsided more rapidly in the above resultant dilute solution of mixed electrolyte than in any single $1/10^3$ molecular solution of sodium or potassium

salts that he had tried. Incidentally, a $1/10^3$ molecular solution of sodium chloride actually retarded the subsidence to some extent. Whilst he did not consider that the sedimentation test could satisfactorily replace elutriation, he thought that, in view of the small amount of apparatus and manipulative skill required, it would appeal more strongly to the practical man, who, if he were a keen observer, might derive much information from it; and that was what was most urgently needed in the foundry to-day.

Mr. J. E. FLETCHER wrote in reply that 30-mesh (not 12-mesh) sieves were used in his experiments. Calibrated tubes with standard water volume had been used, but for works purposes, owing to frequent breakages, he had suggested the less expensive test-tube. He agreed, however, that the measured volume, approximating to a 4-inch depth of water, as a standard, would be more satisfactory in the matter of measuring the approximate voids.

The unit scale for the vertical ordinates in Fig. 1 was 1 inch, the diagram being half full size.

The author wished to correct the reference on p. 154 to the 25 per cent. red and 75 per cent. black used floor sand. That should read "50 per cent. each red and black sand," which mixture corresponded with the sands of low permeability indicated in Fig. 7.

Both milled and hand mixed sands were sedimented in those experiments with similar results, though the milled-mixed samples had been generally taken. The graphs in Fig. 6 were from carefully mixed sands—not milled. With high-clay-content sands half the quantity of sand was used, but he (Mr. Fletcher) agreed with Mr. Holmes that more clearly defined curves were given with the standard 3 inches of sand with 8-inch water column in such cases.

He was interested in the question of the influence of various salts in solution in tap water, and had already obtained very interesting subsidence curve modifications with common salt for example. He thanked Mr. Holmes for his reference to that fascinating problem of colloidal influence on the clay grade subsidence.

Iron and Steel Institute.

SOME OBSERVATIONS ON THE EFFECT OF
SMALL QUANTITIES OF TIN IN STEEL.

By J. H. WHITELEY, F.I.C. (SALTBURN), AND A. BRAITHWAITE, F.I.C.
(EAGLESCLIFFE).

ALTHOUGH important quantities of detinned sheet in the form of bundle scrap have been used for many years past in the manufacture of steel by the open-hearth processes, comparatively little attention has so far been given to the effect of this material on the finished product. The use of such scrap always causes a small percentage of tin to be present in the steel, for it does not appear possible to remove it completely from the relatively large bulks operated on in the detinning plants. The amount remaining is variable, but there is seldom less than 0·05 per cent. and frequently more. Considerable difference of opinion seems to exist among steel-makers as to the advisability of using scrap of this kind in steel production; while some assert that it is harmful, others apparently believe that it has no ill effect.

Tin is rarely, if ever, to be found in iron ores, and when present in steel must consequently have been derived from the scrap used. Experience indicates that practically the whole of the tin thus added to the charge is retained in the steel and is not removed either by the slag or by volatilisation. Nor does it appear necessary that it should be actually in combination with the sheet. The authors have recently observed instances in which the tin was present within the bundles largely as a constituent of a dark brown powder or sludge, apparently due to insufficient washing, and the use of 40 per cent. of this scrap in the charge gave up to 0·30 per cent. in the steel.

A summary of the few investigations which have been made on the effect of tin in steel is contained in a paper given by Dr. Stead a few years ago on "The Influence of Some Elements on the Mechanical Properties of Steel."¹ Briefly, the work there recorded showed that sensible quantities of tin raised both the

¹ *Journal of the Iron and Steel Institute*, 1916, No. II.

yield point and maximum stress and also increased the hardness of steel when hot. Ledebur found that 0.1 per cent. in low carbon steel raised the breaking point 1.4 ton and reduced the elongation by 0.8 per cent. Dr. Stead doubts whether 0.05 per cent. is harmful for plates, rails, and heavy forgings, but states that more research is needed before any definite conclusion can be reached.

The authors' attention was recently drawn to the seemingly deleterious effect of tin in steel through the failure under the drop test of a number of 100 lb. flat bottom basic steel rails in the manufacture of which a certain amount of detinned scrap had been used. These rails were singularly brittle; quite a number failed to withstand the test, which consisted in placing a length of 6 feet across bearings 3 feet 6 inches apart and subjecting it to the blow of a 1-ton weight falling from a height of 30 feet. The fractures were reported as frequently occurring at the supports, and thence travelled apparently along the flange into the web. Except for the presence of tin up to 0.1 per cent., the composition of these rails was practically identical with that of many thousands of tons which had previously been made by the same process and found quite satisfactory.

It should perhaps be mentioned that these tests were all made during a period of wintry weather when the temperature was frequently below zero, and although 100 lb. rails rolled to this particular chemical specification had been tested under similar conditions in previous years without failure, it seemed possible that frost might be the cause of the trouble. In order to ascertain, therefore, whether this was the explanation, suitable lengths of the faulty rails were normalised and again tested at ordinary temperature. The results were far from satisfactory, for some of the lengths still broke, and it was clear that this treatment had failed to eliminate entirely the brittleness.

Macroscopic examination gave no indication of any pronounced segregation in the rails when the usual tests were applied, and, judging from the appearance of the fractures, the grain size in each instance was quite normal. Moreover, no rokes or other defects which might lead to failure could be detected on the surfaces after the scale had been removed, nor did the fractures appear to have originated in this way. Microscopic

examination of sections cut from different parts of the rails likewise failed to afford any explanation of the brittleness. Fig. 1 (Plate III.) shows the appearance of a brittle specimen under a magnification of 280 diameters, and Fig. 2 that of a section of a non-brittle 100 lb. rail free from tin. The structures, which consist of a network of ferrite enclosing areas of fine lamellar pearlite, are almost identical and typical of this class of steel. An example of the fine pearlite present in the former is shown in Fig. 8 (Plate IV.). Further, very few slag inclusions were to be observed, and the most careful examination under a high magnification did not reveal the presence of any minute cavities or flaws; the steel appeared to be sound and of good quality.

Since no elucidation of the problem could be found by the above means, it began to appear probable that the brittleness was due to the presence of tin in the steel. Further, a comparison of the mechanical properties of several of these rails and of non-brittle rails free from tin seemed to support this explanation, for in certain respects the tin-free steels were decidedly superior. Typical results obtained from two samples of each kind are given below, and the analyses of the four samples are recorded in Table I.

TABLE I.

No.	C.C.	Si.	P.	S.	Mn.	Sn.	Cu.	As.	Cr.	Ni.
1	0.54	0.09	0.025	0.057	0.74	nil	0.03	0.035	0.065	0.016
2	0.58	0.14	0.025	0.047	0.79	nil	0.032	0.034	0.070	0.019
3	0.56	0.11	0.036	0.056	0.77	0.076	0.03	0.026	0.070	0.024
4	0.58	0.12	0.023	0.051	0.79	0.084	0.032	0.034	0.085	0.019

Bend Tests.—Length strips of equal size, $\frac{1}{2}$ inch thick, were cut and then bent until fracture occurred. The test showed plainly that the steels not containing tin were the more ductile, for these pieces could usually be bent through 170° , whereas the others seldom passed 120° .

Tensile Tests.—The following results were obtained, the chief feature of which is the low elongation of the steels containing tin.

TABLE II.

No.	Maximum Stress. Tons per Square Inch.	Elongation per Cent. in 3 Inches.
1	50·8	16·5
2	51·2	15·0
3	53·0	5·0
4	52·2	5·0

Izod Impact Tests.—Sections were first prepared with a V-notch of standard size. The energy absorbed in breaking, however, was in all cases too small to allow a satisfactory comparison to be made. A fresh series was therefore taken and tested with a V-notch $\frac{1}{32}$ inch deep; this was found to be more suitable. The figure given in Table III. is, in each instance, the average of at least two tests. A second series of results was also obtained by first oiling the pieces and then allowing them to stand for half an hour before testing in a freezing mixture at about -10° C. The values for these are also given in Table III., and it will be seen that, in both series, the steels not containing tin gave the best results.

TABLE III.

No.	15° C.		-10° C.	
	Head.	Flange.	Head.	Flange.
1	18·5	27·0	14·5	18·0
2	14·0	17·5	14·0	15·5
3	12·0	12·5	11·0	12·5
4	10·0	8·5	7·5	11·0

The inferior quality of samples 3 and 4 revealed by the above tests could only be accounted for by the presence of tin in the steels, and it thus seemed reasonable to conclude that the brittleness under the drop test was really due to this cause. Moreover, this conclusion seemed to be supported by the fact that when the use of scrap containing tin was discontinued no further trouble was experienced.

An endeavour was next made to ascertain directly the effect

of tin in small quantities on the mechanical properties of rail steel. For this purpose three small ingots from the same heat were cast, adding to two of them amounts of tin approximately equal to 0.1 and 0.2 per cent. respectively. This was done in the following manner. Three 150-lb. brass-foundry crucibles were heated for half an hour or so over coke fires and then placed in position as the furnace was tapping. After several ordinary ingots had been teemed the ladle was placed over the crucibles and the first was filled without any addition of tin. As the second began to fill, a rod of tin sufficient to give 0.12 per cent. in 150 lbs. was held in the stream of metal by means of a long pair of tongs and allowed to melt at a fairly steady rate, so that when the crucible was full only the small end held by the tongs was left. To the third crucible, roughly 0.2 per cent. of tin was similarly added. The steel did not set rapidly, and subsequent tests showed that a moderately good distribution of tin in both ingots had been obtained in this way.

When cold the ingots were stripped and removed to the blacksmith's shop, where they were forged down to billets of suitable size for rolling. Finally, they were reheated and rolled into flat bars $3\frac{1}{2}$ inches by $\frac{1}{2}$ inch in section, and allowed to cool together on the mill floor. Every precaution was taken to ensure, as far as possible, equal heat treatment throughout. No tin was present in the cast as tapped, but it was afterwards found to contain rather more nickel and chromium than was present in the rail steels previously considered. The analysis of the steel is given in Table IV.

For the mechanical tests the middle portion of each bar was selected, as it was thought that the distribution of the tin would be more uniform here than at the ends. Several determinations for tin were made on drillings taken from different parts of these lengths, and the results showed that the tin content did not vary more than about 0.05 per cent. in either. The figure recorded in Table IV. is the average result in both cases. A number of tests were also made in which the distribution of tin across the bar was examined. The amount present near the surfaces was repeatedly found to be less than that in the central part around the axis, from which it was concluded that tin tended to segregate.

TABLE IV.

Bar No.	C.O.	Si.	P.	S.	Mn.	Ni.	Cr.	As.	Cu.	Sn.
1	0.61	0.14	0.031	0.055	0.78	0.16	0.14	0.025	0.021	nil
2	...	...	...	...	...	...	...	...	...	0.12
3	...	...	...	...	...	...	...	...	...	0.20

Sections from the middle lengths, when etched and examined under the microscope, appeared to be identical in every respect. Fig. 3 (Plate III.) shows the structure of bar 3, and Fig. 7 (Plate IV.) the fine lamellar pearlite which was present.

For the bend tests two lengths 13 inches long from each bar were taken. Bending at once revealed a striking difference. No. 1 pieces bent through 180° and did not break; those from No. 2 broke before 180° was reached; pieces from No. 3 at about 80° . A photograph of these bends is given in Fig. 6. The effect of annealing was also tried. Three strips were heated to 840°C. , cooled in the furnace, and then bent, but this treatment made no apparent difference; as before, the brittleness increased with the tin content.

The results obtained by the other methods of testing are given in Table V. Taken as a whole they appear fully to support the conclusion, previously reached, that even a small quantity of tin in medium carbon steel is harmful.

TABLE V.

No.	Brinell No.	Max. Stress. Tons per Sq. In.	Elongation per Cent. in 3 Inches.	Reduction in Area per Cent.	Izod Test. $\frac{1}{2}$ Inch V-notch.
1	241	53.5	19.0	34.5	12.0
2	241	53.2	5.0	5.6	12.0
3	260	52.6	5.0	6.0	6.0

It should be remarked here that no difficulty in rolling either the rails or the bars was experienced; the presence of tin did not seem to affect the plasticity of the steel at rolling temperatures. This, however, was not the case with mild steel used for the manufacture of plates. Here, red-shortness was very pro-



FIG. 1. Steel Rail, tin 0.076 %
× 280.

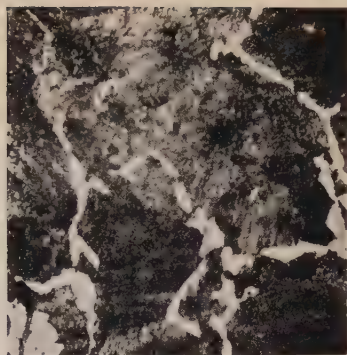


FIG. 2. Steel Rail, no tin. × 280.



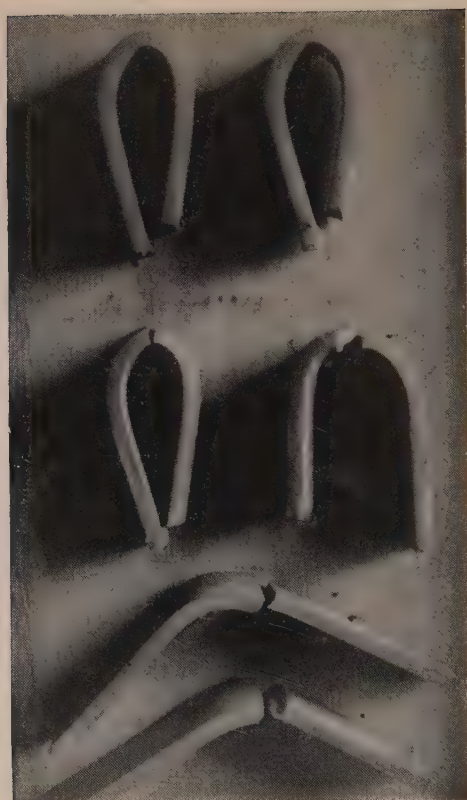
FIG. 3. Steel Bar, tin 0.20 %.
× 130.



FIG. 4. Steel Plate, tin 0.31 %.
× 130.



FIG. 5. Steel Plate, no tin. × 130.



← Tin.

← Nil.

← 0.12 %.

← 0.20 %.

FIG. 6.

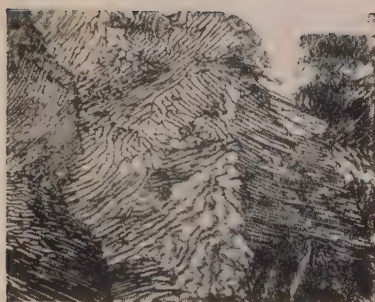


FIG. 7. Steel Bar, tin 0.20% (etched with Picric Acid). $\times 1050$.

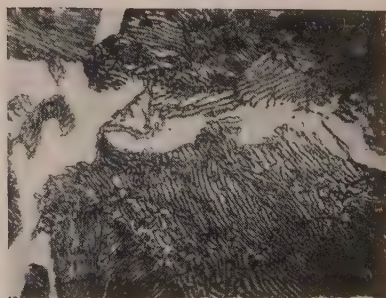


FIG. 8. Steel Rail, tin 0.076% (etched with Picric Acid). $\times 1050$.

nounced when the tin content exceeded 0·15 per cent.; ingots weighing 5 and 7½ tons cracked badly in cogging, and the metal in its behaviour was very reminiscent of that described by Jones,¹ which contained 0·7 per cent. of tin. In the present case, the highest content of tin observed was 0·31 per cent. The usual mechanical tests did not show that 0·3 per cent. of tin had any deleterious effect on plates ½ inch or less in thickness. Bends both length and cross were quite satisfactory; but with thicker plates cross bends especially were often decidedly brittle when the tin content exceeded 0·20 per cent. The results given by two plates, 7⁄8 inch thick, rolled in the same mill and similar in composition, except that one contained 0·31 per cent. of tin, are recorded in Table VI.

TABLE VI.

No.	C.C.	Si.	P.	S.	Mn.	Sn.	Cu.	As.	Max. Stress. Tons per Sq. In.	Elonga- tion per Cent. in 8 Inches.	Brinell No.	Izod Test. ½ Inch V-notch.	
												Lgth.	Cross.
1	·165	·02	·074	·066	·55	nil	·047	·031	30·2	24·0	130	65	42
2	·17	·02	·069	·060	·55	·31	·030	·048	33·8	21·0	156	17	13

The impact figures, in each case, are the average of three closely agreeing results. In Figs. 4 and 5 (Plate III.) the structures of the plates are shown under the same magnification. No. 1 plate has the larger grain size, yet proved, notwithstanding, to be much more resistant to shock.

SUMMARY.

Experimental evidence is advanced showing that the presence of small percentages of tin in medium carbon steel is liable seriously to impair its ductility, so that in rails even 0·06 per cent. may be unsafe. The harmful effect of tin apparently increases with the carbon content, for in mild steel the above amount has, apparently, no detrimental effect. The degree of brittleness produced by tin appears to be influenced also by the heat treatment given; it may be remarked here that several

¹ *Journal of the Iron and Steel Institute*, 1916, No. II. p. 89.

observations have been made which suggest that, in investigating the effect of tin, factors such as the finishing temperature and the amount of work applied to the metal in rolling or forging must not be overlooked.

The authors wish to express their indebtedness to Mr. H. B. Toy and Mr. J. L. Smith of the British Chilled Roll and Engineering Co. for generous assistance afforded in making the impact tests.

APPENDIX.

THE ESTIMATION OF SMALL QUANTITIES OF TIN IN STEEL.

By J. H. WHITELEY.

Since methods for the estimation of small amounts of tin in steel are seldom included in manuals dealing with iron and steel analysis, it was thought that the following description of a method which has been found to work satisfactorily might be useful.

Dissolve 10 grammes of drillings at about 90° C. in 100 cubic centimetres of hydrochloric acid (1·16 sp. gr.) and 50 cubic centimetres of water. When solution is complete, add another 50 cubic centimetres of water and pass a rapid stream of sulphuretted hydrogen through for a few minutes. This serves to precipitate the arsenic and some of the copper, while the tin remains in solution. Filter the hot liquid through a paper into an 18 oz. beaker, taking care to allow the whole to pass through before adding the washings. Boil off the sulphuretted hydrogen, add about 200 cubic centimetres of cold water, and neutralise with ammonium hydrate. Just redissolve the precipitated ferrous hydrate in hydrochloric acid and precipitate the tin as sulphide. Collect the precipitate on a pulp filter and wash repeatedly with a 2 per cent. solution of hydrochloric acid to remove completely all iron salts. Place the pulp in the beaker and pour through the funnel into the beaker a mixture of 40 cubic centimetres of bromine water, a few drops of bromine, and 5 cubic centimetres of hydrochloric acid. Bring the liquid to the boil and gently drive off most of the bromine ; filter by suction and

wash well. The filtrate contains the tin present in the sample. As a precaution, however, it is as well to dry and ignite the pulp in a porcelain basin; there should, of course, be no appreciable residue.

There are several ways in which the tin may now be estimated; of these the two following have been found to give very good results with samples containing known quantities.

(1) *Volumetric*, as described by Ibbotson and Aitchison.¹—Place the filtrate in a conical flask of about 500 cubic centimetres capacity, add 50 cubic centimetres of hydrochloric acid, and boil down to about 40 cubic centimetres. Add 20 cubic centimetres of hot water and 0.5 gramme of finely powdered antimony. Boil the liquid for a few minutes and then cool it in an atmosphere of hydrogen. Titrate the cold solution with N/10 iodine. A blank test should be made on the acid used.

(2) *Gravimetric*.—Bring the filtrate to the boil and add a slight excess of ammonium hydrate. Filter the white precipitate of stannic hydrate and wash the paper twice with water. Dry the paper in a porcelain basin and ignite, first at a low red heat in plenty of air over a bunsen burner, and then in a muffle at a bright red heat. Weigh as SnO_2 . When copper is present in appreciable amounts, a little cupric hydrate is usually precipitated with the stannic hydrate, giving it a bluish colour. This may be removed either by dissolving the precipitate off the paper in hot dilute hydrochloric acid and reprecipitating with ammonium hydrate, or by heating the ignited residue in strong nitric acid until it is quite white. If the latter course be adopted, the filtrate should be diluted and rendered slightly alkaline with ammonia to make sure that no tin has passed into solution.

¹ "Analysis of Non-Ferrous Alloys," p. 106.

CORRESPONDENCE.

SIR ROBERT HADFIELD, Bart., F.R.S., Past-President, wrote that through the kindness of Mr. J. H. Whiteley he had been able to examine two of his specimens, one of which contained tin and the other was almost identical in analysis, except that no tin was present. In view of Mr. Whiteley's interesting results on the embrittling effects of a small percentage of tin, as illustrated by the tensile and Izod tests, he had made a number of shock tests on bars which Mr. Whiteley supplied, using the Frémont machine. His results were contained in Table I., where it would be seen that the materials were tested in the condition as received from Mr. Whiteley, and also after heat-treatment, as both specimens in the condition received were too brittle for their qualities to be differentiated accurately in a nicked shock test. Tensile tests on the two materials after having been heated to 830°C . and cooled in air were also determined. It would be seen that the amount of tin (0.14 per cent.) present in specimen "A" did not appear to be detrimental, though as a matter of fact the "no nick" Frémont test in the condition "as received" was inferior to the specimen containing no tin. The shock test on the materials after receiving identical quenching and tempering treatments did not show any detrimental effects of the tin, in fact, rather the reverse. The tensile tests carried out on the normalised materials were practically identical for the two specimens.

In comparing the results on the small pieces which he (Sir Robert) had tested with those obtained on bars by Messrs. Whiteley and Braithwaite, it was necessary to bear in mind that mass effect might prevent a strict comparison even after the same heat-treatment; in other words, the test-pieces which were cooled in air most probably cooled down much more rapidly than the bars.

Mr. B. YANESKE (Sheffield) wrote that some months earlier he was consulted with regard to the failure under the falling weight test of a considerable number of acid steel tires and rails. The cause of those failures was subsequently traced to the deleterious effect of the presence in the steel of 0.07 to 0.18 per cent. of tin derived from badly detinned sheet scrap which had been used in making up the charges concerned. Upon sampling from the same delivery of scrap, some of it was found to contain as much as 0.44 per cent. tin.

He thereupon made a survey of all the literature he could collect relating to the influence of that element in steel, and was astonished to find how few were the investigations recorded. When the quantity of detinned scrap used in various steel-making plants was considered, many instances of steels possessing abnormal mechanical properties

TABLE I.—*Tests by Sir Robert Hadfield on Steels supplied by Messrs. Whiteley and Braithwaite.*
 Specimen "A" containing tin.
 Specimen "B" without tin.

Specimen Mark.	Analysis.						Treatment.	Férmont Shock Test.				Tensile Test.					
	C.	Si.	S.	P.	Mn.	Sn.		Notched.	Ball Hardness.	No Notch.		Yield Point.	Maximum Stress.	Elongation per Cent.	Reduction of Area per Cent.		
										Kgm.	Angle.					Kgm.	Angle.
" A " D3088f	0.59	0.12	0.049	0.033	0.73	0.14	As received	1.6	1½°	251	12.0	30°	...	...	...
D3089f	"	260	...	...	...	...	...
" B " D3090f	0.60	0.12	0.050	0.035	0.74	nil		1.4	1°	253	22.0	55°	
D3091f	850° oil 700° air	...	...	260	...	...	...	...	...
" A " D3092f		3.7	8°	247	38.3	107°	
D3093f	"		
" B " D3094f		2.2	3°	258	39.4	117°	
D3095f	830° air	...	...	...	...	...	...	...	...
" A " A4062f	35.8	58.0	20.0	40.8	
" B " A4063f	"	32.8	58.0	20.0	42.8		

due to the unexpected presence of tin, such as that described by Mr. Jones, which Dr. Stead referred to in his paper on "The Influence of Some Elements on the Mechanical Properties of Steel,"¹ might be expected. Therefore it was surprising that more research on the subject had not been undertaken, and it was gratifying to find Messrs. Whiteley and Braithwaite adding to the meagre amount of literature available, by their present valuable contribution.

Ledebur's investigation² appeared to show that the presence of tin in mild steel slightly increased the ultimate tensile strength and diminished the elongation, but from his higher carbon series very little could be deduced, for the steels he dealt with were not comparative, neither were they commercial. Guillet's experiments³ were also of little commercial value, whereas Messrs. Whiteley and Braithwaite's observations were very useful to steel-makers. As Messrs. Whiteley and Braithwaite had stated in their present paper, the degree of brittleness occasioned by the presence of tin in the steel would depend on the heat treatment, but he (Mr. Yaneske) had found that the effect of annealing medium carbon steel containing tin depended upon the amount of that element in the steel, and when about 0.15 per cent. or more was present, no matter how the steel was heat-treated, it was impossible to obtain the same degree of ductility as tin-free steels of otherwise similar composition in their normal condition. Although from his own observations he would have expected the influence of tin to be to diminish the elongation to a considerable extent, it was remarkable that the authors found that 0.08 per cent. tin in about 0.56 per cent. carbon rail steel had the effect of reducing the elongation from 15 to 5 per cent.

The tables opposite give some results obtained during the investigations he had referred to on similar steels to those examined by the authors.

While those results showed that the presence of tin caused the ductility to be considerably diminished, the influence on the elongation was less than that obtained by Messrs. Whiteley and Braithwaite. The tires containing tin showed numerous small cracks on the flanges, whereas no cracks were observed in the rails. From Messrs. Whiteley and Braithwaite's results and his (Mr. Yaneske's) own observations, there was no doubt that the presence of tin was very harmful to the ductility of medium carbon steel, and that its influence increased with the carbon content.

MESSRS. J. H. WHITELEY and A. BRAITHWAITE, in a written reply, expressed their indebtedness to Sir Robert Hadfield for the careful tests he had made on the two pieces of experimental bars which were sent to him. His results on bar "A" after both quenching and normalising, while somewhat surprising, were of much interest and

¹ *Journal of the Iron and Steel Institute*, 1916, No. II. p. 89.

² *Stahl und Eisen*, 1901, vol. xxi. pp. 330-1.

³ *Revue de Métallurgie*, 1904, No. 1, p. 500.

Acid Tire Steel.

Composition per Cent.										Mechanical Properties.													
										Normal.			Annealed at 850° C.										
										Maxi- mum Stress, Tons per Sq. Inch.	Elonga- tion per Cent. in 2 Inches.	Reduc- tion of Area per Cent.	Maxi- mum Stress, Tons per Sq. Inch.	Elonga- tion per Cent. in 2 Inches.	Reduc- tion of Area per Cent.								
Average of normal tin-free tires										0.55	0.79	0.279	0.036	0.038	0.14	0.08	nil	52.5	16.0	26.0	...	...	...
Tires containing tin { 1. 2. 3.										0.54	0.77	0.306	0.035	0.039	0.10	0.08	0.078	52.8	10.75	16.8	50.7	13.5	18.6
										0.56	0.81	0.297	0.037	0.039	0.16	0.12	0.126	54.3	8.0	11.3	53.5	10.25	15.2
										0.55	0.77	0.284	0.039	0.042	0.13	0.10	0.150	54.2	5.5	5.9	54.7	6.0	6.5

Acid Rail Steel.

	Composition per Cent.								Mechanical Properties.					
									Normal.			Annealed at 850° C.		
									Maxi- mum Stress. Tons per Sq. Inch.	Elonga- tion per Cent. Inches.	Reduc- tion of Area Cent.	Maxi- mum Stress. Tons per Sq. Inch.	Elonga- tion per Cent. Inches.	Reduc- tion of Area per Cent.
Average of normal tin-free rails	0.49	0.77	0.126	0.028	0.053	0.024	0.026	nil	45.2	18.5	31.5	...	...	...
Rails containing tin { 1. 2. 3. 4.	0.50	0.76	0.112	0.029	0.055	0.028	0.018	0.072	46.7	11.75	17.7	46.0	15.5	23.0
	0.48	0.75	0.135	0.025	0.055	0.030	0.026	0.094	46.3	10.5	14.8	46.4	14.5	21.1
	0.51	0.79	0.121	0.027	0.051	0.022	0.020	0.135	46.6	8.0	10.3	45.2	11.0	14.7
	0.50	0.77	0.103	0.029	0.056	0.024	0.025	0.178	47.2	6.5	6.9	46.6	7.5	9.3

value ; for, although a certain amount of evidence came to hand during the investigation indicating that the degree of brittleness due to tin depended, to some extent, upon the heat treatment given, such a marked variation as existed between their results and Sir Robert's was not anticipated. The effect of normalising was especially noteworthy, but it should not be overlooked that the necessarily small test-pieces used would cool in air decidedly quicker than the original bars as, indeed, Sir Robert Hadfield remarked. The increase in the maximum stress from 54 to 58 tons of itself strongly supported that conclusion. Since rails, plates, &c., were not usually subjected to further heat treatment after rolling, very little attention was given to that aspect of the subject in the paper, but the observations were confined almost entirely to steel in the condition as rolled, and the authors were satisfied, from the work done, that tin could, under such conditions at any rate, cause brittleness in steel. Sir Robert Hadfield's results, however, necessitated a further investigation, which was at present in progress. The results so far obtained showed that, in normalising, the rate of cooling was an important factor when tin was present. For example, it had been found that strips of the 0.20 per cent. tin bar would bend through 160° if quickly air-cooled after heating to 830° C., whereas, if allowed to cool slowly in the furnace, at a rate of about 3° per minute, between 750° C. and 650° C., they snapped at once on attempting to bend them. There could thus be little doubt that the explanation of those wide differences between their results and Sir Robert's was to be found in variations in heat treatment, especially as regards the rate of cooling.

They were likewise indebted to Mr. Yaneske for the very interesting results given. On the whole, they appeared to confirm completely those recorded in the paper. The more pronounced diminution in the elongation due to tin found was most probably caused, as indicated above, by a somewhat slower rate of cooling of the samples. The subject was one that still required a great deal of investigation, and Mr. Yaneske's contribution should prove useful to future workers in that direction.

Iron and Steel Institute.

THE PRODUCTION OF SINGLE METALLIC CRYSTALS AND SOME OF THEIR PROPERTIES.

BY PROFESSOR H. C. H. CARPENTER, F.R.S. (ROYAL SCHOOL OF MINES).

THE following paper has been written at the invitation of the Council of the Iron and Steel Institute, following on a suggestion made by Dr. Hatfield at the last Annual Meeting, that it would be of interest to some of the members if Miss Elam and the author would prepare a paper dealing with the production and properties of single metallic crystals. It so happens that since the beginning of July Miss Elam has been engaged in work at the Cavendish Laboratory, Cambridge, arising directly out of the investigations referred to, and it has not, therefore, been possible to prepare a joint paper on the subject. With her consent, however, the author has undertaken to present an account of their investigations, and it must be understood that, so far as the experimental results are concerned, the following paper is, strictly speaking, joint work. Miss Elam, however, is not necessarily committed to the acceptance of the views stated therein, which are an interpretation of those researches.

As a result of a large number of experiments extending over some years, Miss Elam and the author succeeded, about two years ago, in preparing very large crystals of the metal aluminium, and worked out the conditions under which such crystals could be regularly produced. The discovery, therefore, was not a chance one, but was simply the last of a series of experiments logically connected together. Emphasis is laid on this point because, whether the reasoning which led to this result be correct or not, it at any rate produced the desired result. Full information as to these researches will be found in the two papers specified in the footnote,¹ together with a review of other investigations

¹ "Crystal Growth and Recrystallization in Metals," *Journal of the Institute of Metals*, No. 2, 1920, pp. 83-131. "The Production of Single Crystals of Aluminium and their Tensile Properties," *Proceedings of the Royal Society*, 1921, vol. c., A, pp. 329-353.

bearing on the same subject. The present paper does not attempt to cover this ground so completely, and those who are sufficiently interested are referred to the papers in question. All that is attempted here is to give a succinct account of the results achieved, and a brief discussion of their theoretical aspects.

Metals and alloys are composed of aggregates of crystals. Attention is drawn to two of their characteristics. In the first place, they do not, as a rule, possess plane faces—that is, the external forms of crystals. They are joined together at boundaries which have been produced by the meeting of a number of crystals growing simultaneously, and are usually irregular in outline. It is generally assumed that crystallisation starts in the liquid metal or alloy from a number of centres, and proceeds with a velocity and in a manner characteristic of the metal and conditions under which it is being cooled. The resulting boundaries may approximate to plane surfaces, but are more usually curved and irregular. These crystals are called “allotriomorphic,” to distinguish them from “idiomorphic” crystals, which do possess plane faces, and are characteristic of mineral substances and artificially prepared salts.

In the second place, they are usually very small and cannot be distinguished without the aid of a microscope. It is true that, in the case of large castings weighing many tons, crystals of several cubic inches capacity have been formed and subsequently isolated. The great majority of metals and alloys, however, which have been cast and hot-worked, have from 150 to 300 crystals to the linear inch. This means that in all such cases there will be from 3,375,000 to 27,000,000 crystals in a cubic inch. Frequently, however, the size is even smaller, especially in the case of steels. The crystals are still more minute in severely drawn wires, and from figures given by Sykes ¹ it appears that in molybdenum wire there may be as many as 5000 to the linear inch.

The properties of metals and alloys are the properties of these aggregates of minute crystals. Sauveur ² was the first investi-

¹ *Bulletin of the American Institute of Mining and Metallurgical Engineers*, vol. ii., No. 6, February 1921.

² *Proceedings of the International Association for Testing Materials, Sixth Congress*, vol. ii., No. 6, 1912.

gator to show, about eleven years ago, that by carefully straining and subsequently heating metals much larger crystals can be produced, and suggested that there was a critical stress which produced the largest crystals. As subsequent events have shown, this suggestion is perfectly correct. Subsequently other investigators, notably Rüder, Chappell, Jeffries, and Hanson, showed that if a metal was locally deformed and then heated exceptionally large crystals were formed at some distance from the point at which the strain is severest. Seligman and Williams,¹ working in the author's laboratories some years ago, stretched aluminium sheet to various degrees, and found on heating that up to a certain point deformation had no effect. Beyond this large crystals were formed, and as the deformation was further increased the crystal size was diminished.

About two years ago we succeeded in converting the whole of the parallel portion of aluminium test-pieces, whether in the form of sheets or bars, into a single crystal, which indeed extended for some distance up into the curved shoulders of the test-pieces, forming an irregular boundary line. The crystals varied in size from 0.5 to 2.0 cubic inches, and it has been possible to compare some of their properties with those of the aggregates of small crystals of which this metal is usually composed. Experiments have also been carried out with silver, copper, and iron, but with less success, although in all three cases it has been possible to grow crystals very much larger than those contained in the original metal.

The steps which have led to the production of these very large crystals cannot be understood without a brief reference to certain results established in the paper on "Crystal Growth and Recrystallization in Metals," already referred to. These results are :

1. In the absence of a change of phase, neither crystal growth nor recrystallisation will take place in a metal unless it has been plastically deformed and subsequently heated to a certain minimum temperature and for a certain minimum time.

2. The largest crystals are always formed at the minimum stress requisite to produce growth, which minimum is determined by the temperature of heating.

¹ *Journal of the Institute of Metals*, No. 2, 1918, vol. xx. pp. 162-165.

3. The lower the temperature of heating, the greater the stress required to produce the largest crystals obtainable at that temperature.

4. There is no gradual increase in size from the original crystals up to the largest; the latter appear to form directly from them.

5. Test-pieces of aluminium strained and heated at a low temperature, which nevertheless is sufficient completely to soften the metal, *e.g.* at $350^{\circ}\text{C}.$, show no crystal growth at that temperature. Nevertheless, if subsequently heated at a higher temperature, they produce large crystals equal in size to those normally produced at that temperature for the same degree of strain.

6. In our experiments growth always took place by boundary migration and not by coalescence.

7. Crystals can both grow and be grown into at one and the same time.

8. A large crystal may grow at the expense of a small one, and a small crystal may grow at the expense of a large one.

9. Neither similarity nor diversity of orientation affects the growth of one crystal into another.

It will be seen from this that in the production of large crystals of aluminium, the adjustment between mechanical strain and temperature of heating is extremely important.

This point is clearly illustrated in Plate V., which shows how the crystal size may be varied in aluminium according to the degree of strain. The eight test-pieces shown, after a preliminary heat treatment to remove work-hardness and render the crystals equiaxed, had been subjected to degrees of strain varying from 2 to 10 per cent. extension on 3 inches of the parallel portion of the test-piece. After this, they were all heated to $550^{\circ}\text{C}.$ and kept there for six hours. Finally they were etched in a 10 per cent. solution of caustic soda. It will be seen that the crystals in the test-piece extended 2 per cent. are very coarse, and that as the strain is increased the crystal size diminishes, until at 10 per cent. it has become quite small. But there is a further point to be noted, *viz.*, that in all the eight cases shown large crystals have also formed in the broad heads of the test-pieces where the strain must have been less.

We have studied the structural changes produced in a crystal aggregate by deformation, followed by heat, very carefully. They may be summarised broadly in the following way: The first effects of strain are slight. They are revealed by the presence of slip-bands, and, in some cases, twinned crystals. The former are completely, and the latter to some extent, removed by heating. No change is observed in the shape of the crystals. The boundaries appear unaffected, and, apart from twinning, there is no change in orientation. Thus far, only the interior of the crystals is affected. Somewhat greater deformation, however, followed by heat, produces actual crystal growth, and at this stage the boundaries of the crystals become active. The activity is shown in the capacity of the growing crystal to push forward its boundary in certain directions, thus invading other crystals, but even at this stage the orientation of the growing crystals is maintained. That of the crystals grown into is of course destroyed, unless it happens to be the same. A still greater deformation produces the third stage, which appears to take place exclusively in the boundaries of the deformed crystals. It is here that new crystals are born, indicating the destruction of the original crystals and the production of a new orientation. Whereas, therefore, the early effects of deformation are shown only in the interior of the crystals, the later ones appear to take place entirely at the boundary. Accordingly, it will be seen that, from the point of view of producing large crystals from an aggregate of small ones, the intermediate degree of strain just referred to is the important one.

THE PRODUCTION OF SINGLE CRYSTALS IN ALUMINIUM SHEET.

The problem which we set ourselves was to convert the crystals in the parallel portion of a test-piece 4 in. \times 1 in. \times 0.125 in. into a single crystal. These test-pieces were machined from a hard-rolled aluminium sheet and subsequently heated. After this treatment, which produced complete recrystallisation, there were about 150 crystals to the linear inch. Calculation shows, therefore, that the total number of crystals contained in the parallel portion of the test-piece was about 1,687,000. The experiments have been carried out with metal of the highest

purity obtainable (99.6 per cent.). In order to convert the parallel portion of these test-pieces into a single crystal three treatments are necessary, two of them thermal and the third mechanical. The sheet as received was in the cold-rolled condition, the crystals being very much elongated and worked into one another. It had first to be heated, so that it might be completely softened and new equiaxed crystals of approximately uniform size produced. It had next to be strained to the required amount, and finally it had to be heated so that the potentiality of growth conferred by strain could be brought fully into operation. The details of these three treatments are summarised in the following paragraphs:

(1) *The Temperature and Time of Heating before Stressing.*—The most suitable temperature was found to be 550°C. , and the time six hours. If the heating was continued longer large crystals formed on the surface of the sheet in many cases and the test-pieces were rendered useless, because the stress subsequently applied produced a greater elongation, which was localised to a large extent in these crystals, and consequently the strain was not uniform. If heated at a lower temperature, the crystals finally produced for a given load and elongation were similar, but the results were very variable.

(2) *The Stress applied and the Percentage Elongation caused.*—In the earlier experiments the method adopted had been to stretch the test-pieces in tension by a given amount, measured by means of dividers on 3-inch gauge marks. This method was not capable of very accurate adjustment, and was discarded in favour of pulling with a given load and then measuring the extension. The advantage of this method was that the strain was always constant, and the variations in elongation were very slight. Moreover, a large number of test-pieces could be stretched with ease and rapidity. The procedure finally adopted was to pull to some definite fraction of a ton per square inch, which would give approximately the required elongation. A load of 0.20 ton, i.e. 1.6 ton per square inch, gave an elongation of 0.8 per cent. on 3 inches. If such a test-piece was subsequently heated large crystals were produced, but some small surface crystals frequently remained unabsorbed, even after many hours heating at 550° to 600° . A load of 0.30 ton finally proved the

most suitable. This is equivalent to 2.4 tons per square inch, and gave an average elongation of 1.6 per cent. on 3 inches.

(3) *The Temperature of Heating after the Application of Stress.*—It was found that large crystals began to form usually at about 500°C. , or even lower in some specimens, but not until 520° in others, although the treatment had been identical in all cases. It was also found that the lowest possible temperature at which growth took place at all was the most suitable for growing the largest crystals. Consequently each test-piece was placed in a furnace whose initial temperature was 450°C. , and the temperature raised at about 20° to 30° per day up to 550°C. It was then subsequently heated for one hour at 600°C. in order to complete the absorption of small crystals on the surface, which persistently remained at lower temperatures. This method proved on the whole to be the best, but even so, on an average not more than one test-piece in four is converted into a single crystal over the parallel portion, the boundaries at each end extending in an irregular manner into the wide heads. The time required for a single crystal to form from the 1,687,000 originally present can only be stated approximately, for it has been found to vary within tolerably wide limits, and, as just mentioned, some of the small surface crystals only disappear after fairly prolonged heating, but in the majority of cases the result can be achieved in from 72 to 100 hours. A test-piece is, of course, much more quickly converted into three or four large crystals than into one, since in the former case growth takes place simultaneously from several centres.

Certain variations of the above methods were subsequently tried, but none of them was found to give greater regularity of results, although some of them established facts which bear on the question of how single crystals are actually produced. Prolonged heating at a low temperature, or starting the heating from a low temperature, *e.g.* 250°C. , and gradually raising it, was not found to affect the crystal size. It was established that if the test-pieces were more severely stressed the temperature at which the maximum crystal size was produced was lowered. It was therefore to be expected that, provided the temperature at which heating was commenced was sufficiently low, all the test-pieces within certain limits of stress should give the same

sized crystals on heating. A series of test-pieces was stretched 1, 2, 3, 4, and 5 per cent., heated at 250°C ., and the temperature then raised to 550°C . In the pieces stretched from 1 to 4 per cent., the number of large crystals produced was approximately the same, although certain differences were manifest. In that stretched 5 per cent., however, the crystals were much smaller, indicating that, however much the temperature may be lowered, there is an upper limit to the stress which will produce the largest crystals.

If the optimum conditions for the production of a single crystal throughout the parallel portion of the test-piece are maintained, on an average one experiment in four is successful. There are, however, considerable variations from batch to batch, *e.g.* in a given case eighteen test-pieces, which had received as nearly as possible the same heat and mechanical treatment, gave the following results, which must be understood to refer only to the parallel portion of the test-piece 4 in. \times 1 in. \times 0.125 in. Two test-pieces consisted of one crystal, six of two crystals, five of three crystals, three of four crystals, and two of six crystals. In another batch, out of twenty test-pieces, seven consisted of one crystal, eight of two crystals, four of three crystals, and one of four crystals. The best result hitherto achieved has been in a batch where nearly half the test-pieces were converted into a single crystal over the length in question.

TENSILE STRENGTH TESTS.

When composed of small crystals (about 150 to the linear inch), as obtained by heating for six hours at 550°C ., the sheet gives uniform results on breaking. The ultimate stress varies from 4.5 to 4.7 tons per square inch, and the percentage extension on 3 inches from 36 to 38. The sheet necks slightly at the fracture, which is usually straight. This is the standard of comparison from which the behaviour of single crystals may be judged. Its condition may be regarded as "normal," and a photograph is given in Plate VII., No. 12. The roughening of the surface, due to the large number of small crystals, is evident.

The values obtained in tests of specimens consisting of single crystals varied from 2.80 to 4.08 tons per square inch, while

the extension varied from 34 to 86 per cent., measured on 3 inches. These variations in properties were accompanied by differences in the method of stretching and the types of fracture, and these have provided a means of classifying them. In certain cases the mechanical properties, especially the extension, were found to be closely related to these characteristics. Speaking broadly, five types may be distinguished.

Type I.—The test-pieces narrowed in breadth gradually from the shoulders towards the fracture. The reduction in breadth near the fracture was often great, e.g. the metal necked sometimes almost to a point (Plate VI., No. 2). The sides



DIAGRAM I.

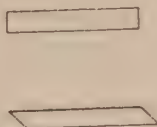


DIAGRAM II.

(machined edges of the sheet) remained perpendicular, and the reduction in thickness was only from 2 to 3 per cent. Slip-bands were usually absent from the surface, but large slips were frequent near the fracture, forming steps on the sides and similar markings on the face. It was noticed in some specimens that a large slip occurred over one half, and this then held, while a similar slip took place on the other half. The process was then repeated until the test-piece broke (Diagram I.). Slipping in this case took place in the direction of pulling, and at right angles to the plane of the sheet. With a view to following the distortion of the specimens during the test, some of them were ruled into squares (0.25 inch) by means of a fine needle point. The results showed that the squares became diamond-shaped (Diagram II.), and that they had both narrowed and elongated, and at the fracture the lines at right angles to the axis were frequently bent at an angle of 45° . Nos. 1 and 2 (Plate VI.) are examples of this type, and

No. 16 (Plate VII.) shows the change in the shape of the squares. The tenacity was found to vary in the case of seven tests from 2.9 to 3.9 tons per square inch, while the elongation varied from 57 to 67 per cent.

Type II.—In this case the test-piece remained broad, losing sometimes only 1 per cent. in breadth, but became very thin, with a uniform reduction of thickness of about 45 per cent. The sides tended to slope slightly in the same direction away from the perpendicular. Slip-bands on the surface were well marked, and their main direction was across the test-piece, *i.e.* at right angles to the axis. There was no necking at the fracture. The test-piece remained broad but drew down to a knife-edge, and then parted in a straight line, either at right angles to the axis or inclined at some other angle to it. If the test-pieces were marked in 0.25 inch squares before being pulled, the lines at right angles to the axis did not become inclined to the same extent as in specimens of Type I. They merely drew farther apart, while the position of the lines parallel to the axis did not alter. Although the squares were only lightly scratched on the surface with a needle point, the cross lines affected the internal fracture to such an extent that they were revealed on the opposite side of the test-piece by means of interruptions in the slip-bands (No. 7, Plate VI.). This phenomenon was only met with in specimens of this type, and is no doubt due to the particular direction of the slip-bands in relation to the stress. This type, therefore, shows slipping in the plane of the test-piece in the direction of the stress (Nos. 7 and 8, Plate VI.). Tenacity values obtained in these tests varied from 2.8 to 3.3 tons per square inch, and the extension from 47 to 74 per cent.

Type III.—In this case the test-piece both narrowed and thinned uniformly. There was no necking at the fracture which went straight across the test-piece, as in Type II., either at right angles to the axis or inclined at some other angle. A noticeable feature of this type is the sloping of the sides so that the section after pulling is no longer a right angle, but a parallelogram, with alternate acute and obtuse angles. The sideways slipping which causes the test-piece to take this form was entirely absent from Type I., and only slightly evident in Type II. It always occurs in this group, but not always to the same extent. Slip-bands

were usually well marked, and were inclined to the axis at different angles. Squares marked on the specimens by a needle point both narrowed and elongated and became diamond-shaped, owing to the lines at right angles to the axis inclining towards it. Although similar in that respect to Type I., they differed in that the diamonds were more uniform in size and shape over the whole test-piece. In other words, the elongation was more general and uniform. This type, in contradistinction to the two previous ones, shows slipping in two main directions. It elongates in the direction of the stress, by slips nearly parallel with the plane of the sheet, and also at right angles to the plane of the sheet but parallel with the axis. Inasmuch as these planes are not at right angles to the direction of the stress, there is always a sideways slip as the crystal endeavours to accommodate itself to it, and this accounts for the change in shape of the cross-section of the test-piece. There are greater variations in tensile properties in this than in any other group—the values for ultimate stress ranging from 2·9 to 4·1 tons per square inch, while the extension over 3 inches varies from 34 to no less than 86 per cent. Examples will be found in Nos. 3, 4, and 5 (Plate VI.).

Type IV.—This combines the qualities both of Type I. and Type III., in that the test-pieces not only narrowed and thinned but, in addition, necked at the fracture. In all cases a sideways slip was evident. The values of tensile strength were remarkably uniform, varying from 3·1 to 3·3 tons per square inch, while the elongation ranged from 53 to 75 per cent. An example of this type is seen in No. 6 (Plate VI.), while Nos. 14 and 15 (Plate VII.) show the distortion of the 0·25 inch squares as a result of the strain.

Type V.—In this class are included all the test-pieces which produced twin crystals on being pulled. No signs of these were visible before stress was applied. In some cases only a few resulted, while in others the test-piece was twinned all over. In every case the test-piece buckled and crumpled to a certain extent, owing to the shifting of portions of the sheet into a twinning position. The slip-bands change in direction as they cross a twin boundary, and where the specimen had been marked in squares these also change direction sharply at the twin boundaries.

Two types of twins were met with. The first resembled those produced in tin and zinc, although, owing to the large size of the crystals, they were on a much larger scale. They appeared like large fibres. The fracture across them was uneven, and the thickness of the sheet at the fracture differed from twin to twin. Examples are given in Nos. 9 and 10 (Plate VII.). The second type of twinning observed was one in which the twinning planes were almost straight. Such a twin is shown at the top of the test-piece in No. 11 (Plate VII.). It appears as a narrow dark line starting at the shoulder of the test-piece and running up the centre of the broad end. Twins of this type also formed frequently on each edge of the test-piece. In a given case on one side the entire edge turned up, while the edge on the opposite side turned down. Nos. 17 and 18 (Plate VIII.) show a part of the surface in which, in addition to twinning on the edge, a twin has also been formed at the centre. A section of this crystal (No. 18) shows how the twins at the edges turn in opposite directions, and also the step-up at the twin in the centre. Twinning planes across the crystal are all parallel. This type is similar to that produced by the well-known method of causing twinning in calcite. By pressing a knife on the acute angle of a calcite rhomb near the edge, a portion of the crystal can be bent right over, making a definite angle with the unaltered face. The tenacities in this class varied from 3.0 to 3.8 tons per square inch, and the elongation from 55 to 67 per cent. on 3 inches.

The results are summarised in the following table :

TABLE I.

Type.	No. of Tests.	Tensile Strength. Tons per Square Inch.	Elongation per Cent. on 3 Inches.
I.	7	2.9 to 3.9	57 to 67
II.	7	2.8 „ 3.3	47 „ 74
III.	15	2.9 „ 4.1	34 „ 86
IV.	8	3.1 „ 3.3	53 „ 79
V.	5	3.0 „ 3.8	55 „ 67
Sheet containing 150 crystals to the linear inch	5	4.5 „ 4.7	36 „ 38

STRESS TESTS OF TEST-PIECES CONSISTING OF TWO
CRYSTALS.

Each crystal in a test-piece consisting of two or more crystals behaves according to one of the five types described above, provided that the whole test-piece at the point of fracture consists of a single crystal. A considerable number of specimens composed of two crystals were fractured in tension, and almost every combination of the five types was met with. In the majority of cases tested, the crystals occurred end to end in the test-piece, and fracture always took place across one or other of the crystals, *but never at the boundary*. The influence of one crystal in giving support to the other at the boundary was most marked, and its effect was often noticeable at a distance of 0.25 inch from the boundary. Reduction both in thickness and breadth was much less at this point, and the power to withstand deformation was considerably increased, especially where one crystal slipped to the left and the other to the right. The metal drew down on either side of the boundary and left it as a ridge, sometimes pronounced in thickness, at other times in breadth. In many cases the sheet looked as if it had been twisted in testing. It is not difficult, however, to account for these irregularities, when it is remembered in what different ways the single crystals extended in tension. The crystal which narrowed on pulling, in contact with the one which remained broad, tended to make the latter narrow also, with the result that it frequently wrinkled and twinned in the vicinity of the boundary. In its turn the crystal which remained broad tended to prevent the other from narrowing, and this produced a thickening. Figures of some of these test-pieces show the effects referred to above. In No. 19 (Plate VIII.) will be observed three test-pieces in which the distortion at the junction of the two crystals is very manifest. No. 20 (Plate IX.) gives an edgewise view of five fractured test-pieces in which, in each case, the combination of types there included is mentioned. This shows very clearly the different extents to which the crystals have been distorted, and the influence of the junction.

In those cases where two crystals existed side by side in the test-piece fracture occurred across them, and one crystal

frequently broke before the other. In this case the latter crystal continued to elongate until it also broke, with the result that when the test-piece was subsequently put together there was sometimes a gap of 0.25 inch between the fractured halves of the first crystal. Tests have been carried out on eighteen test-pieces consisting of two crystals. When the test-piece was marked in 0.25 or 0.5 inch squares before pulling, it was possible to measure the elongation on 1 inch in each crystal. These are not strictly comparable, as one of them includes the fracture. In one case, however, the specimen broke outside the gauge marks, and the figures represent the actual elongation of each crystal under the same load :

Total Elongation on 3 Inches.	Crystal No. 1 on 1 Inch.	Crystal No. 2 on 1 Inch.
49 per cent.	71 per cent.	25 per cent.

TABLE II.—*Test-Pieces consisting of Two Crystals.*

Tensile Strength. Tons per Square Inch.	Percentage Elongation on 3 Inches.	Type of Crystals.		Percentage Elongation of each Crystal on 1 Inch.	
		Fractured.	Other.	Fractured.	Other.
3.1	55	IV.	III.	61	52
3.0	38	II.	II.	67	29
3.1	63	V.	II.	71	63
3.2	50	I.	II.	86	29
3.1	51	II.	II.	81	17
3.5	55	II.	III.	94	17

PRODUCTION OF SINGLE CRYSTALS IN ROUND BARS.

One-inch diameter bars of the same purity as the sheet were used. Two sets of test-pieces were machined from them, the diameters being 0.564 and 0.798 inch respectively. These were heated at 550° C. for six hours and given an extension of 2 per cent. on 3 inches, and heat treatment as in the previous tests. This treatment was successful. On one occasion, out of eighteen test-pieces, eight consisted entirely of a single crystal over the whole parallel portion. It extended up into the shoulders of the test-piece, where an irregular boundary was formed. Three others were monocrystalline, except for one or

more small crystals which intruded at the shoulders. Table III. gives the mechanical properties of some of the crystals obtained. As in the case of the sheet, the properties vary considerably in different specimens, the tenacities ranging from 3.0 to 4.0 tons per square inch, and the elongations from 55 to 87 per cent. in the case of single crystals. No. 10, which had an elongation of 87 per cent. before fracture was quite completed, is comparable with the value of 86 per cent. obtained with a single crystal in the sheet. The specimens marked with a star were removed from the machine at different stages before fracture was complete, so as to study the method of fracture. The elongations are therefore lower than they would have been if the two halves had actually parted.

TABLE III.

No.	Tensile Strength. Tons per Square Inch.	Percentage Elongation on 3 Inches.	Number of Crystals in Bar.
1	3.4	76	One crystal.
2	3.0	76	One crystal and small one at shoulder.
3	3.0	78	„ which twinned on pulling.
4	3.1	68	„ and small crystals at shoulder.
5	4.0	71	„
6*	3.3	56	„
7*	3.5	60	„ and small one at shoulder.
8	3.9	55	„ and two small ones one end.
9*	3.8	65	„ and small one at shoulder.
10*	3.06	87	„
11	3.4	59	Two parallel crystals, fracture across two.
12	3.7	40	Two small parallel crystals at one end; the rest consisted of one crystal in which fracture occurred.
13	3.4	66	Three crystals, fracture in one.
14	3.1	64	Two parallel crystals at one end; the remainder consisted of one crystal in which fracture occurred.
15	3.3	69	Two crystals, fracture across one.
16	3.1	77	„ „ „ „
17	3.5	50	One crystal at each end, and one in the middle, across which fracture occurred.
18	3.3	50	Two crystals, fracture across one.
19	4.82	44	Bar consisting of small crystals heated six hours
20	4.88	44	at 550° C.

The table also contains values found in test-pieces consisting of two or three crystals. The last two values are those obtained for bars containing the usual number of small crystals in the

annealed condition, *i.e.* about 150 to the linear inch, or 3,500,000 in a cubic inch.

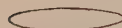
Except that some of the crystals twinned on pulling, while others did not, there were no different types of fracture such as were found in the sheet, but the deformation of the test-piece was very remarkable in all cases and deserves special mention. On the one hand, the bar consisting of small crystals drew down in the ordinary way with a roughening of the surface, a cup-and-cone fracture, and the maintenance of a circular cross-section. On the other hand, the single crystals flattened very much in



1.



2.



3.

DIAGRAM III.



1.



2.



3.



4.

DIAGRAM IV.

one dimension, whereas the other dimension differed but little from the original diameter of the bar. Diagram III. shows (1) a section of the original bar, (2) a section after pulling so as to cause considerable distortion, and (3) a section at the fracture. The end result was not a cup-and-cone fracture at all, but what may be described as a double groove. The method of fracture was very peculiar, and can best be described with the aid of diagrams. When the bar began to break it drew down sharply in the same direction in which it thinned, and a lens-shaped area was formed (Diagram IV., Fig. 1). As the bar pulled apart this became smaller and smaller (Fig. 2). It parted first at each side, and then in the middle (Fig. 3). A section cut through the fracture illustrates the thinning at right angles to the plane, depicted in Figs. 1, 2, and 3, and shows the curious double-grooved fracture with flow lines, which was always obtained (Fig. 4).

This type of fracture was found in all the bars where fracture actually occurred across single crystals. Photographs of some of these bars are given on Plate IX., No. 21. In the case of each pair one-half of the test-piece is placed so as to show the broad side, while the other half is turned at right angles to show how it thinned.

Considerably more difficulty was experienced in converting the crystals in the 0.798 inch diameter bar into a single crystal. After several attempts, however, bars were obtained in which single crystals extended over the entire cross-section. In one case the whole of the parallel portion of the test-piece was found to consist of one single crystal, while in several others more than three-quarters of the parallel portion was thus occupied. Many of the bars consisted of two crystals, but in the majority of cases these existed side by side and not end to end, so that fracture always occurred across both of them. Most of these bars twinned on pulling, so that the fracture was often uneven and did not show the definite shape obtained in the 0.564 inch diameter bars. In addition to the above, 1 inch square bars were treated. Owing to the shape, however, these failed to strain uniformly, and on heating crystals grew from the four corners and met in a line in the middle of the four sides. Some of the crystals were from 2 to 3 inches long, and were visible on two adjacent sides. Remarkable effects were obtained on breaking these. In some places the corners became rounded, while in others they were narrowed to a ridge, almost of knife-edge thickness. The whole bar became very much twisted and distorted. Attempts were made to measure the Brinell hardness number on two adjacent sides of the same crystals. The lowest available load, however, was 500 kilogrammes, and the depression made was so large, owing to the softness of the metal, that it could not be made on one side without affecting the other. It was, however, possible to make depressions in some crystals which were sufficiently near the centre of the bar to obviate all risk of being affected by the edges. These were not round, as is the case with metal consisting of small crystals. Most of them were almost square with rounded corners, but they differed from crystal to crystal according to the orientation. Diagram No. V, shows Brinell depressions produced in three crystals,

When, as in certain cases, the pieces broken in the tensile tests were heated, recrystallisation was brought about. The temperature at which this began, and the size of the new crystals produced, depended on the amount of deformation of each particular crystal. Those which had been least deformed produced the largest new crystals. It was always found that the new crystals grew from the region of maximum stress, *e.g.* from the fracture itself, from scratches on the surface, and from crystal or twin boundaries. On heating a broken single crystal the smallest of the new crystals are found at the fracture, and the size increases up to the shoulders, where the stress has been least.

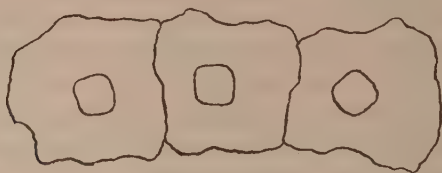


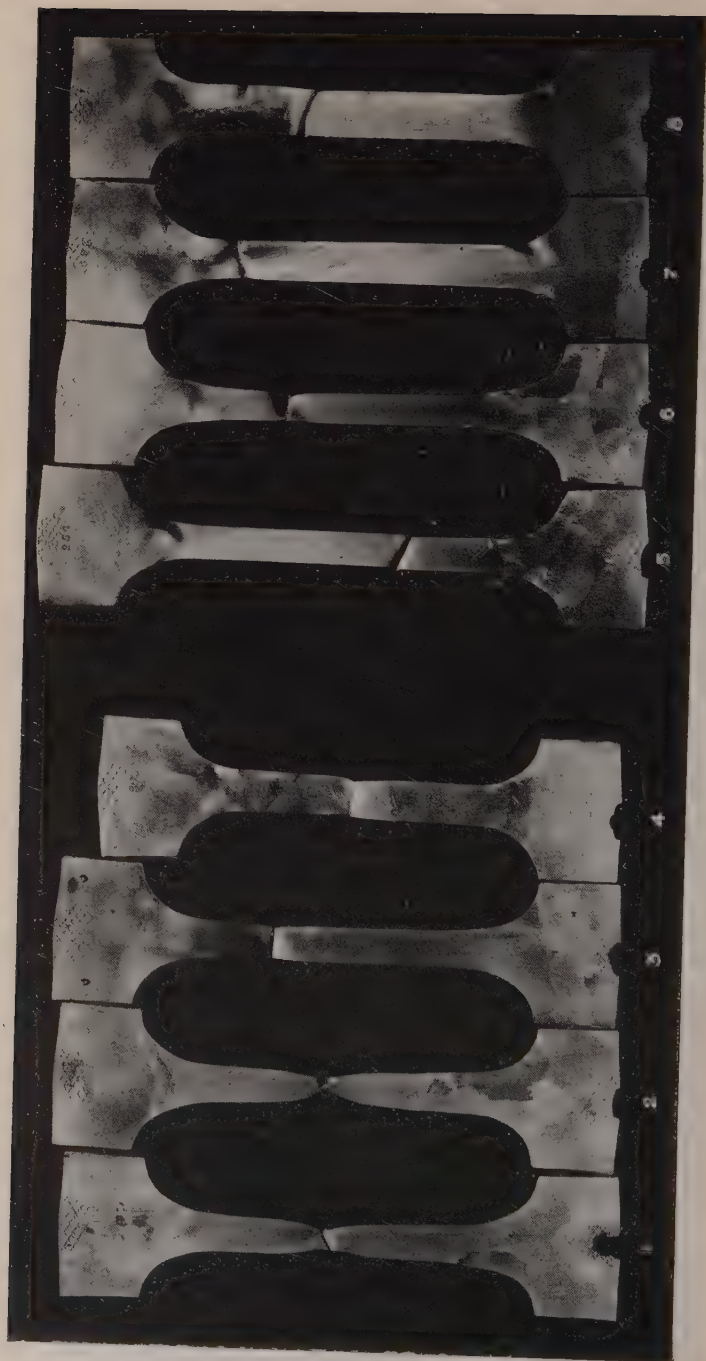
DIAGRAM V.

The new crystals were elongated in the direction of pulling, but frequently sloped sideways, as if following the direction of the slip-bands. Some of the new crystals showed well-marked twins, resembling those in copper and brass, and one example was obtained in which the twinned crystal completely penetrated the sheet.

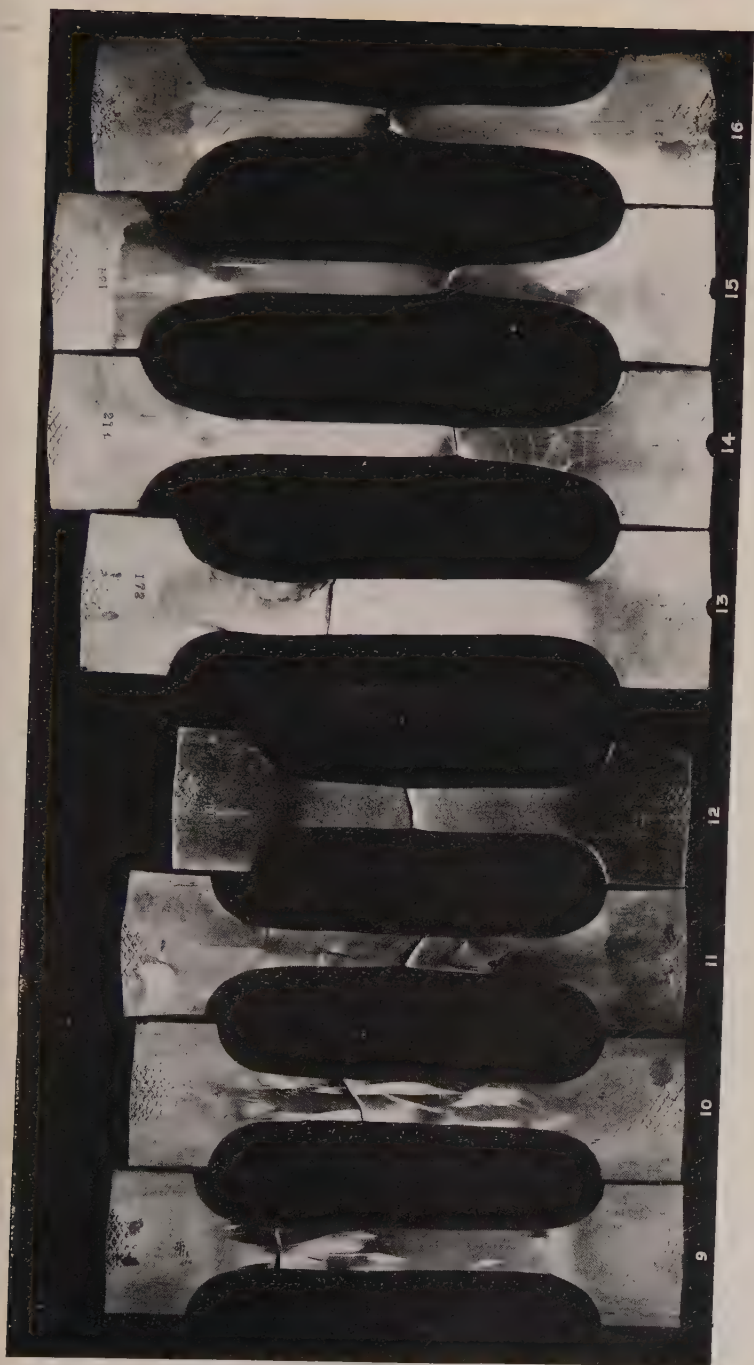
The foregoing is an account of the tensile tests carried out by Miss Elam and the author on single crystals, both in the sheet and in bars. The numerical values obtained refer only to the end results, and the description of the method of distortion has been purely qualitative. A very interesting and detailed investigation, however, has recently been carried out at Cambridge by Mr. G. I. Taylor and Miss Elam, on the distortion of one of these crystals during a tensile test. The results formed the subject-matter of the Bakerian lecture delivered before the Royal Society on February 22, 1923. The precise object of the test was to determine the nature of the distortion which occurs when a crystal of aluminium is extended by a direct pull, and to find out the relations between the direction of the pull and the orientation of the crystal axes.



Showing diminishing size of crystals with increase of strain in the parallel portion of the test pieces.



Showing various types of fracture of single crystals in the parallel portion of the test pieces.



Showing various types of fracture of single crystals, except in the case of No. 12, which consists of the usual number of small crystals (about 3,500,000 in a cubic inch).



No. 17 shows three twin crystals—one at each edge and the third in the middle.

No. 18 shows the "step-up" in the middle twin.

Fractures of two crystals (end to end in the parallel portion of the test piece).



Side view of test pieces consisting of two crystals end to end, broken in tension.

Fractured test pieces of single crystals in round bars, showing how in each case the bar draws down in one dimension and produces a wedge-shaped (double-grooved) fracture.

A rectangular specimen, $1 \times 1 \times 20$ cm., was cut from a round bar of aluminium which had been treated by our method, so that it consisted of a single crystal. This was stretched through successive extensions of 5, 10, 20, 30, 40, 60, and 78 per cent. of the original length when the crystal broke. At each stage of the test the distortion was determined by measurements of scratches which had been ruled on the surface, and, at the same time, the directions of the crystal axes were determined in each case by X-ray analysis. To quote Mr. Taylor's words: "The method developed for determining the nature of the distortion, by which any configuration of the specimen was strained into any other, was to find lines of particles which were unextended by the strain. The directions of these lines lie on a quadric cone, which evidently has two positions corresponding with the two configurations from which it was derived. On applying this method to the specimen under consideration, it was found that for all stages of the extension up to 40 per cent. elongation, the 'unextended cone' was of a degenerate form, consisting of two planes, one of which contained in all cases the same particles, while the other contained different particles for different strains. The former plane was evidently undistorted during the whole strain up to 40 per cent. elongation, and this distortion was due to slipping or shearing over this plane. The orientation of the crystal axes was determined by X-ray measurements, and it was found that the slip plane was identical with an octahedral (111) plane of the crystal. The direction of the shear was also determined, and found to be along one of the three principal lines of atoms in the octahedral plane. When the specimen was extended beyond 40 per cent. elongation, it was found that the distortion was no longer due to slipping on one plane. This was explained by showing that the effect of the shear was to rotate the axis of the specimen relative to the crystal axes in such a way that another (111) plane came into a position where its inclination to the axis was the same as that of the slip plane. Under these circumstances slipping might occur on both planes simultaneously, and it was verified that this was the case."

These conclusions drawn by Mr. Taylor are of the utmost interest, and the author would like to draw particular attention to one of them, viz. that when the second plane comes into position,

after the 40 per cent. extension, slipping occurs on both planes uniformly. It would doubtless have been expected by most metallographers that during the 40 per cent. extension, when slipping occurred on one plane, a certain amount of hardening would have taken place on it, and that when the second plane came into play, after the 40 per cent. extension, the slipping would not have been even. Mr. Taylor's conclusions, therefore, are of very great interest in their bearing on the theory of hardening by cold-work. It certainly seems to be established that when the second plane came into the requisite position as a result of shear, slipping took place equally on both planes, whose hardness was therefore the same.

Mr. Taylor and Miss Elam are carrying out investigations of the distortion of other single crystals prepared by our method. It should be added that the X-ray analysis of the distortion of the crystal was rendered possible by a method worked out by Dr. Müller at the Cavendish Laboratory, to whom we are much indebted, and it is to be hoped he will publish a full account of this before long.

Ever since these single crystals became available, it has been the author's wish that as many of their properties as possible should be determined. Foremost among these come the elastic constants. With regard to these, the co-operation of the author's colleague, Professor Dalby, of the City and Guilds Engineering College, Imperial College of Science and Technology, and of Dr. Stanton at the National Physical Laboratory has been of great assistance. With their assistance Young's modulus of elasticity, and the limits of proportionality of a number of single crystals under tensile stress, have been determined and compared with those of the aggregates of small crystals (150 to the linear inch) contained in bars as ordinarily prepared. In addition, Dr. Stanton and Mr. Gough have ascertained the fatigue limits of some of our single crystals and compared them with those of aggregates. It is hoped shortly to publish these results, but it may be said they indicate that the single crystals are not isotropic, and that the properties vary according to the orientation of the crystal.

Miss Elam and the author have carried out compression tests on both round and square bars, in order to ascertain whether large

crystals can be produced after deformation by compression, followed by heat treatment. The maximum length of test-piece possible for a square bar of 1 inch diameter section was 6 inches for a compression of 1 per cent. measured on 3 inches. Greater compression and longer test-pieces resulted in the bending of the bars. In round bars of 1 inch diameter, the maximum length was found to be 5 inches for a compression of 1 per cent. On heating these test-pieces, large crystals were produced in all cases. A cross-section of the round bars showed them to consist of not more than three crystals in most cases. The square bars had a core of small crystals surrounded by four large crystals, which met in the centres of the faces of the square. Some of these crystals were 3 or 4 inches long. It is clear from these tests that the capacity of aluminium to form large crystals is not the result of tensile strain *per se*, but is the result of strain generally.

The very high figures of percentage elongation obtained when some of the single crystal test-pieces were broken in tension showed that the metal in this form was extremely ductile, far more so than when the test-piece consisted of the usual number of small crystals (about 3,500,000 per cubic inch). This has been confirmed by experiments on rolling and drawing single crystals. In a given case, a crystal was rolled down from the original thickness (4 in. \times 1 in. \times 0.125 in.). At a certain stage, when it had elongated considerably, it was cut in half and one of the pieces was rolled down to 0.0094 inch, corresponding to a reduction in thickness of 93 per cent. This rolling was done without any annealing. The strip was still quite malleable, and the operation could have been continued further had the rolls permitted it. This malleability is far in excess of that in the sheet consisting of small crystals.

Wire-drawing is an extremely severe form of mechanical work, and experiments with single crystals showed that these could be drawn from a diameter of 0.564 inch to 0.02 inch and still remain very ductile. In order to obtain a sufficient length of bar for this purpose, test-pieces 16 inches long were prepared with a parallel portion of 6 inches (diameter, 0.564 inch). Five such bars were completely converted into a single crystal over the parallel portion. In a given case, a test-piece was machined

3.5 inches long and 0.4 inch in diameter. This was drawn down cold to a length of about 112 feet. After this process it was still sufficiently ductile to pass the Post Office test for aluminium wire. Further experiments are being carried out to ascertain the extent of the hardening during the wire-drawing of single crystals, and comparing it with that of a bar containing the ordinary number of small crystals. In any case, it seems clear that the single crystals of aluminium possess remarkably high malleability and ductility in the cold, and that use might well be made of these properties in manufacturing operations.

Something must now be said about the crystallography of aluminium. Crystals are usually classified according to their external geometrical form, to which their properties are found to be closely related. This method cannot be applied to determine the system to which metallic crystals, produced as above, belong, since they do not possess the external forms of crystals, but take their shape from the test-pieces in which they are grown. As stated, the single crystals grow well up into the heads of the test-piece, and the boundary is clearly shown on etching with a suitable reagent (a 10 per cent. aqueous solution of sodium hydrate). Under these circumstances, the whole area of the crystal reflects the light uniformly. We utilised these etching properties in coming to a decision that we were dealing with single crystals. Considering, however, that this was the first time that such relatively enormous crystals had ever been prepared artificially, we felt that it was essential to check our conclusions by an independent authority who used a different criterion. Accordingly, we sent to Professor Sir William Bragg a number of test-pieces, some of them consisting of the micro-crystalline aggregate, while others were composed of what we regarded as single crystals. He kindly submitted these to an X-ray analysis, which enables the space lattice of the crystals to be determined, and with it the crystalline symmetry. His experiments completely confirmed our conclusions, that we were really dealing with single crystals. Moreover, since then, a further confirmation has been obtained by the experiments of Dr. Müller, already referred to. Hull¹ was the first to investigate the structure of aluminium crystals in a finely crystalline aggre-

¹ *American Institute of Electrical Engineers*, vol. xxxviii., Part II., October 1919.

gate, and concluded that the pattern thus obtained corresponds to a face-centred cubic lattice, *i.e.* the grouping of the atoms is such that there is one at each corner of the cube, and one in the centre of each face, making a total of fourteen in all. This corresponds, as Colonel Belaiew¹ has recently pointed out, to an octahedron situated within a cube. Sir William Bragg and Dr. Müller have confirmed this for our single crystals. They belong, therefore, to the cubic system, and must have properties consistent with those of that group which possesses the highest degree of symmetry both external and internal. Investigations of the crystals in this system indicate that, as regards certain properties, they are isotropic, while as regards others they are anisotropic. In the former category come the properties of conducting light, heat, and electricity, and the coefficient of expansion. In the latter are grouped elasticity, cohesion, and the conduction of sound. In such cases, however, the properties are closely related to the symmetry, since the maximum and minimum values have been found to coincide with axes of symmetry. Accordingly, the variations in the tensile properties of the test-pieces which have been described are due to differences of cohesion in different planes, which do not all contain the same number of atoms. Although the single crystals obtained in the sheet and bars were formed in the same shaped test-pieces in both categories, it was obvious that their original orientation, relative to the axis of the test-piece, varied considerably. Indeed, it may not have been precisely the same in any two of the cases tested. The shape of both sheet and bar alters when stress is applied, since slip and deformation take place only on certain planes, and the changes in shape observed correspond to the attempt of the crystal to accommodate itself to the stress. Such changes were much greater in some tests than others. Jeffries and Archer² recently predicted what the shape of a square test-piece should be after being pulled, supposing that it consisted of a single crystal, and that the planes of slip (shear) were at an angle of 45° to the stress. They concluded that a test-piece should reduce in thickness in one dimension only, and that the fracture should be wedge-shaped. Every one of the bars tested

¹ *Journal of the Institute of Metals*, No. 1, 1923.

² *Metallurgical and Chemical Engineering*, vol. xxi., No. 24, June 15, 1921.

by us shows a wedge-shaped fracture. It is quite certain that the original orientations relative to the axis of the test-piece were not all identical. This means, therefore, that, under the stress, some of the bars must have altered their shape considerably in accommodating themselves to it. This was actually observed, because in certain cases they pulled out with a uniform thinning in one plane; while in others a considerable twist took place. The extreme variations in cohesion found in single crystals produced in the sheet were 2.8 to 4.1 tons per square inch. In the bar they were 3.0 to 4.0. It is somewhat surprising that the cohesion of the sheet composed of three and a half million crystals to the cubic inch is not higher than 4.66 tons per square inch, for it has usually been supposed that metals owe much of their cohesion to the fact that they are aggregates of small crystals oriented at haphazard, and consequently that slip can only occur to a very limited extent, viz. along the planes of those particular crystals which happen to be placed in the direction of minimum cohesion relative to the stress, and that the adjacent crystals, more favourably placed for resisting the stress, support them. It will be seen that the highest value of cohesion obtained for a single crystal in the sheet was nearly 90 per cent. of that of the microcrystalline aggregate, while in the case of the bar it was 82 per cent.

Two questions now come up for consideration: (1) Why do abnormally large crystals form on heating after a small deformation, and gradually decrease in size as the deformation increases? and (2), to take the extreme case, why, after a particular degree of deformation, is it possible to form a single crystal from an aggregate of several millions? It will be convenient to consider these questions in the order mentioned.

As mentioned on p. 179, the first effect of small amounts of deformation by tensile stress is to produce slip-bands and in some metals twins, but provided the stress does not exceed a certain value, this is all that happens. Very little more deformation, however, causes a change in a few of the crystals, so that on heating they grow. At present it is not known what this change is; but whatever it be, the less the strain the fewer the centres from which growth will start, and hence the larger the crystals ultimately formed. In a given case the largest crystals

began to appear after 2 per cent. elongation, followed by heating at 550°C ., but their capacity for growth was exhausted when only about one-half of the total number of crystals had been absorbed. At 645° , however, they were able to effect complete absorption, owing to the greater mobility conferred by the higher temperature; but in its turn, the higher temperature enabled the growth to start from more centres, so that actually the final crystal size was smaller than at 550°C . As the deformation is increased, more crystals will be strained to the critical amount to produce growth on heating, and there will accordingly be a corresponding decrease in crystal size. This corresponds to the effects observed. In all these cases the microcrystalline aggregate, after the test-piece has been strained, is in the plastic condition. Knowledge of this subject at the present time rests principally upon the well-known researches of Sir George Beilby. According to him, when once the plastic state is reached, vitreous amorphous films are formed along certain planes in the crystals. It might be considered that the crystal growth observed on heating the strained test-pieces was connected with some property of these films. This is why we carried out the experiments summarised on p. 178, in which test-pieces of aluminium were strained and heated at 350°C . This is sufficient completely to soften the metal, and therefore, by hypothesis, to reconvert the vitreous amorphous films into the crystalline state. At this temperature no crystal growth is observed. If, however, test-pieces were afterwards heated at 550°C ., they produced large crystals equal in size to those normally produced at that temperature for the same degree of strain. These experiments show conclusively that a vitreous amorphous phase has nothing whatever to do with the crystal growth observed by us.

For the coalescence of the minute crystals in the test-pieces into large crystals, there is one condition which we regard as essential, viz. that all the crystals must be in a strained condition. Our own experiments have shown that, in the absence of a change of phase, crystal growth will not take place in a metal unless it has been plastically deformed and subsequently heated to a certain temperature for a certain time. As confirming this view, it should be pointed out that there was nearly always a strip of small unaltered crystals on either side of the flat ends of the

test-pieces, even when they had been heated at $645^{\circ}\text{C}.$, and that the large crystals showed no tendency to grow into them. Owing to their position, they had not been strained by the pulling of the test-piece. It seems clear, therefore, that the crystals must be strained to some extent if they are to coalesce after heating.

Coming to the second question, what has to be explained if possible is, why, after a tensile stress producing an elongation of 1.6 per cent. on 3 inches, followed by somewhat prolonged heating at $550^{\circ}\text{C}.$, a single crystal is formed from the large number of small crystals originally present? It is convenient to assume that the orientation of these crystals was quite haphazard before the stress was applied. This explains, as has been mentioned, the fact that such a test-piece is isotropic. The effect of the tensile stress will be to give the crystals a certain small pull in one direction. The conditions for the production of a single crystal from this mixture are considered by Miss Elam and myself to be, that every crystal in the complex must be strained a certain amount, and that one of them is strained rather more than the rest. This particular crystal may be regarded as being in the condition of critical strain, and ultimately all the other crystals align themselves upon it after sufficient heating. When this condition is realised, the test-piece consists of a single crystal. It has been suggested by Mr. U. R. Evans¹ that the least deformed crystals are the most active in crystal growth, and that the more strained crystals align themselves upon them. If this explanation be correct, then it is the least deformed crystal which ultimately imposes its orientation upon that of the others. At present it cannot be stated which of these views, or indeed if either of them, is correct. This is why we have taken up the experimental investigation of the deformation of the test-pieces by X-ray analyses. We are hoping that the result of this will be to show what it is that happens when a test-piece is strained to the critical amount and is subsequently heated. It is very interesting and significant that this method of investigation, so far as it has gone, tends to show that when metallic crystals are plastically deformed the deformation takes place by means of slip on certain planes in a regular manner, and that the structure

¹ *Journal of the Institute of Metals*, No. 1, 1921, vol. xxv. p. 299.

of the crystal is maintained. This has been shown by Mr. Taylor, Miss Elam, and Dr. Müller in the experiments already referred to, and in this case the deformation was carried up to 78 per cent. elongation. Burger¹ has recently studied the structure of drawn tungsten wires by Röntgen ray analysis. He used homogeneous and heterogeneous rays, and obtained concordant results. His conclusion is that the space lattice of tungsten is not altered by drawing, but that in a drawn wire the crystals are directed in such a way that the (110) planes are by preference perpendicular to the axis of the wire, and that after annealing at high temperatures this orientation partly persists. Considering the severity of the mechanical work produced by wire-drawing, this persistence of crystalline orientation is evidence of its great stability.

It can hardly be doubted that the method developed by us of producing very large crystals of aluminium by a combination of mechanical strain and heat treatment is capable of extension to other metals, and, indeed, during the last two years, Miss Elam and I have been working on the metals iron, copper, and silver with this end in view. It is well known that iron can be obtained in the coarsely crystalline condition. The large crystals obtained in the close-annealing of mild steel sheets, and investigated by Dr. Stead, are a case in point. These sheets, after being worked, are heat-treated at about 800° C. The combination of the mechanical strain and heat treatment results in the production of very coarse crystals. Wire-rope which has been severely strained and subsequently heated is liable to be converted into an envelope composed of very coarse crystals containing a core of small crystals. Sauveur produced coarse crystals by a combination of Brinell ball impressions and heat treatment. All these are special instances of a suitable combination of strain and heat treatment. We have carried out some preliminary experiments on iron with the object of obtaining monocrystalline test-pieces. We have found here, as with aluminium, that the condition of the surface of the metal is of great importance, and that the scale present on iron and very mild steel militates decidedly against success. There is a further complication, due to the limit of heat treatment imposed by the α to γ change, at about 900° C. Quite clearly, if it is desired to produce

¹ *Nederlandsch tijdschrift voor Natuurkunde*, Jaargang 1921, 214-218.

monocrystalline test-pieces of α iron, the temperature must not exceed that of the α range.

With regard to copper, we have attained a certain degree of success in the production of coarse crystals, but the streaks of cuprous oxide present in commercial copper are a very great hindrance to the coalescence of the small crystals which have been strained and heated. Accordingly, we have obtained samples of electrolytic copper sheet rolled direct from the cathode metal which are quite free from oxide, and will prove, we hope, suitable for experiments with this metal. Copper, however, shows a complication to which aluminium is much less liable, though it is not entirely free from it, viz. the tendency to form large numbers of twin crystals when the strained metal is heated. This undoubtedly is going to be a difficulty in the production of monocrystalline test-pieces of this metal. Up to the present we have attained more success with silver than with either iron or copper. We have been able to produce crystals of this metal up to $\frac{1}{2}$ inch diameter and $\frac{1}{8}$ inch thickness. Silver can be obtained in a state of high purity and contains no film of oxide, but it shares with copper the tendency to form twin crystals when strained and subsequently heated. I hope before long that Miss Elam and I will be in a position to publish definite experimental results with these metals.

The photographs shown on Plates VI. to IX. are reproduced with the kind permission of the Royal Society.

DISCUSSION.

Dr. C. H. DESCH, F.R.S. (Sheffield), said that the extraordinarily interesting work upon which Miss Elam and Professor Carpenter had been engaged for some time brought before the members the possibility of determining the real mechanical properties of metals. It was known that in any ordinary mass of metals the properties were due in part to the properties of the crystal grains and in part to those of the boundaries. It had hitherto been impossible to separate those two factors. Definite measurements now existed of certain mechanical properties of the crystals, and he understood from the authors that, before long, measurements of other mechanical properties would be available. As it was now possible to prepare test-pieces composed of, for example, two crystals, it was possible to study the behaviour of a single boundary. The work had been so interesting and such great experimental skill had been exercised that it had been a delight to read the paper. It might, perhaps, be of some interest to members to refer to work which had been done on some other metals which seemed to throw light on the process of slipping and deformation generally. In Germany, Polanyi, who approached the subject from an entirely different starting point (since he began by investigating textile fibres), had dealt with cold drawn wires and annealed metals, and succeeded in making test-pieces of single crystals, not as large as those described by the authors, but in a cast condition without having to apply any cold work followed by annealing. Polanyi had made a series of measurements with certain metals, particularly tin, lead, and zinc, and he believed on a few samples of aluminium also. The results obtained in the case of zinc might not be generally known to the members and, therefore, might be worth recording. Zinc in the cast condition was a brittle metal, and a test-piece of cast zinc gave only a small elongation. But if a single crystal rod of zinc were prepared by drawing out a rod slowly from a mass of molten metal, mechanical measurements could be made with some ease.

Slipping, in the case of zinc, took place only on the basal plane, so that although the symmetry of zinc was not as high as the symmetry of aluminium and mathematical difficulty might be expected, actually that rather simplified the measurements because there was only one plane on which slip could occur. Supposing the basal planes in the rod to be inclined to its axis, successive blocks slid over one another retaining their parallelism; and, at the same time, as the stress was applied they tilted round, becoming more nearly parallel to the axis of the test-piece. The chief point of interest was that that tilting could only go on to a certain extent, and when a definite angle was reached with the axis rupture took place. In every case the rod would extend until a

definite angle was reached, which in the case of zinc at room temperature appeared to be 15° . How much elongation could be obtained in the particular specimen depended on the original inclination of the basal planes to the axis. A rod in which they were already inclined to the axis at something less than 15° was brittle and broke without any elongation whatever. When suitably inclined the elongation was very great. Cast zinc would give an elongation up to 600 per cent. or six times its length. At a temperature of 200° it gave elongations up to 1700 per cent. The sections might be regarded as being elliptical blocks lying on one another, and as they slid over one another they still retained their elliptical shape. Therefore the cross section, which was cylindrical to begin with, became an exceedingly flat ellipse, just as in the case of the authors' specimens. Besides the basal plane, there was another set of planes in zinc on which slip could occur to a small extent, the principal prismatic planes. Just before fracture a little slip took place on those planes, producing necking, but it could not go very far, and immediately afterwards the specimen broke. Polanyi's experiments had been checked all through by the X-ray method, and it seemed that the orientation was preserved. Polanyi's work was later in date than that of Miss Elam and Professor Carpenter, who opened up the wonderfully interesting field under discussion, but was begun independently. He was sure the members hoped that the authors would be successful in getting specimens of iron, copper, and similar metals and arriving at their mechanical properties in the same way. Everyone would look forward with the most intense interest to the further measurement of the mechanical properties of those single crystals.

Dr. W. H. HATFIELD (Sheffield) thought the work that Miss Elam and Professor Carpenter had carried out was one of the most fundamental contributions that had been made to metallurgy for many years past. It had been the custom of the Institute and of other Institutions to discuss the properties of metals, and refuge had been sought by various scientists in the formulation of a hypothetical film between the crystals. Whether or not that film existed was still open to demonstration, but during the controversies that had ranged over the last ten or fifteen years members had always had before them X, the metal, and Y, the film, both unknown quantities. Miss Elam and Professor Carpenter were now in a position to say: "Here is X quantitatively." That enabled investigators to deal with the whole problem, and they were in a vastly stronger position than they were up to the time the results of the investigations were published. It might be said that the experiments had only been made with aluminium, but it was quite logical and safe to reason by analogy from one metal to another. If, therefore, the physical characteristics of single crystals in aluminium bore a certain relationship to the physical characteristics of the conglomerate it might well be assumed that somewhat the same relation-

ship existed in iron, a metal which unfortunately the authors had not yet been able to deal with. It was relatively easy, in considering the properties of metals—iron in particular—to postulate that there was an under-cooled liquid film between the crystals. Postulating an under-cooled liquid film of indeterminate thickness and composition it was possible to arrive at any deductions desired. Personally he thought that instead of the explanation of the properties of metals continuing on a purely hypothetical plane they were now in the realm of fact, and by careful consideration of the data which the authors had placed before them, he felt that, after all, the material which constituted the crystal of a metal was that which concerned them most in considering the mechanical and physical properties of metals.

Colonel N. T. BELAIEW, C.B. (London), said that all the members had followed with interest the wonderful experiments which had been carried out by Miss Elam and Professor Carpenter, and later on by Dr. Taylor and Dr. Müller. As Dr. Desch had stated, the importance of the experiments lay in the fact that it was possible to test the mechanical properties of metallic crystals. That afforded an insight, never before realised, into the inner structure of metals. Crystals of such large dimensions were now being obtained that it was possible to test the theories which had hitherto existed, so that the importance of the investigations could hardly be exaggerated.

Aluminium was a metal which crystallised in a face-centred cubic lattice. Some few years ago it would have been said to be a metal which crystallised in octahedra. He desired to draw attention to the question of what a face-centred cubic lattice was. The diagram (Fig. A.) showed a series of fourteen atoms. Six of the atoms gave the figure of a regular octahedron and the other eight were placed in the intersections of the faces of the cube. Some time ago crystallographers who were speaking of substances crystallising in octahedra were always met by the difficulty of what was called the regular filling of space, because it was rather difficult to imagine how octahedra would homogeneously fill the space. In the face-centred cubic lattice the answer was obtained: there were eight supplementary atoms which allowed for the filling of the space. It was apt to be forgotten that when dealing with a cubic space lattice what actually was in question was a substance which crystallised in an octahedron. Octahedral crystals of aluminium could be obtained. Crystals of iron and steel could be obtained as well, which were also octahedral; but in spite of the fact that the cleavage planes and many of the other properties were the properties of an octahedron, the space lattice was a *cubic* space lattice, only with face-centred atoms.

He asked the members to try and realise from the diagram what were the gliding planes and the cleavage planes in an octahedral substance, say in gamma iron. Those planes were best illustrated during the secondary crystallisation in the Widmannstätten figures. The

Widmannstätten figures in martensite were stresses in octahedral planes too. That showed again that nature, when dealing with a face-centred cubic lattice, so arranged that the gliding and slip planes were not the planes of a cube but the planes of an octahedron. Therefore, when dealing with the importance of the mechanical properties, it was always possible to consider from the theoretical point of view what would be the deformation of an octahedron after a certain stress.

The section of an octahedron was represented in the diagram (Fig. B). $\angle CDC'$ would be an angle of $109^\circ 28' 16''$ and $\angle D'CD$ of $70^\circ 31' 44''$. He desired the members to consider the possibility of such a specimen existing where the axis of that specimen coincided with the diameter CC' . The stress S if supplied that way would give two

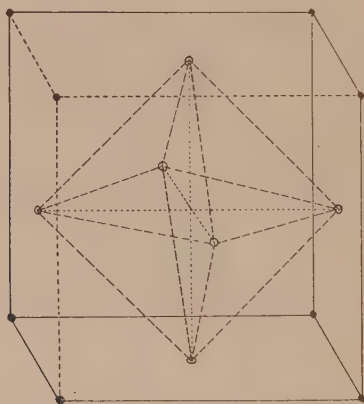


FIG. A.

additional stresses S and S' , a slip on the plane CD , and a slip on the other plane CD' . If it were quite certain that during the experiments the stress was being applied exactly on the line of that axis a regular slip would be expected on the two octahedral planes. What would be the fracture in that case? If the slip occurred on two planes only the fracture would be just like the slip of two packs of cards slipping sideways; it would be what Professor Carpenter called a wedge edge fracture (No. 7, Plate VI.).

He next desired to suppose that the slip occurred simultaneously on both the four octahedral planes. In that case, the result shown in the diagram would be produced. The importance of the mechanical results described in the paper was that they showed, first of all, the important type of fracture No. 1. That was not theory, it was a fact. A fracture was obtained which would correspond with regular deformation, which would run exactly parallel to all the planes of an octahedron. That was type No. 1. Type No 2, as

already shown, would correspond with a case where the slip occurred parallel to two of the octahedral planes.

It could also be imagined next that the axis of the specimen would coincide not with the line CC' , but with one of the edges of the octahedron. In that case it was to be expected that the slip would occur on that plane only. Professor Carpenter's experiments opened up many possibilities in regard to type No. 1 and type No. 2, or a modification of them (type No. 3), because it was possible to get an

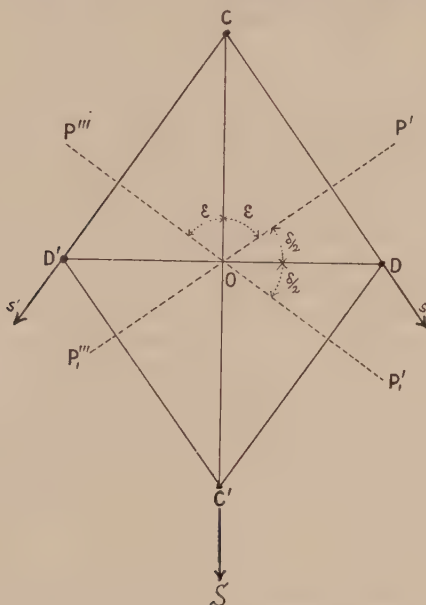


FIG. B.

actual insight into what was happening in the space lattice. But that was not enough. If type No. 1 gave a slip according to the maximum number of octahedral planes, one would expect the crystal to show a certain likeness to that particular type of slip, because it allowed a large number of lines of particles to slip in a regular fashion. What was the reply of the crystal to that? One would expect a certain accommodation of the axes of the crystal with reference to the axes of the specimens; one expected that the crystal would try to accommodate itself exactly in that way, and that was what the experiments had proved if he was right in his deductions. The investigations, undertaken at Professor Carpenter's request by Mr. G. I. Taylor and Miss Elam, had proved that during the tensile tests the angle between the axis of the specimen and between the axis of the octahedron did not remain stationary, its

angle tended to become nil, and the two axes tended to coincide. That was an exceedingly important and interesting fact, and he confessed that he experienced great emotion when he first saw the results that had been obtained.

The authors drew attention to the fact that there was no considerable increase in hardness in the first plane when the slipping changed. He desired to draw attention to some recent work of Dr. Benedicks in that respect. Dr. Benedicks, in one of his recent papers, made a classification of deformation. He stated that, assuming slip bands on a certain plane, the stresses would be considered as being the result of either a parallel translation (like a pile of photographic plates), or what he called the proportional translation. In the latter case there was a definite maximum angle of deformation because the proportional translation, while keeping to the same space, was quite different in the mechanism, because instead of slipping there was twinning, and the angle of the twinning was the determining factor. He thought something of that sort must have occurred in the experiments of Dr. Polanyi which Dr. Desch mentioned. In the particular case under discussion the authors were getting crystals of a very pure aluminium. Dr. Benedicks said that when a very pure material was being used, parallel translation practically always existed and the amount of deformation was practically unlimited; but once there were traces of oxides or of a certain impurity, instead of a parallel translation (owing to twinning), proportional translation occurred, and only then was a certain amount of increase of hardness and of cold work noticeable. The two points he had mentioned seemed to him rather important, not only from the theoretical but the practical point of view, and showed the great possibilities which were now, thanks to the admirable work of Miss Elam and Professor Carpenter, before investigators into the subject.

Mr. E. H. SANITER, Member of Council, said Dr. Carpenter's paper was one of extreme interest. In drawing hard steel wire it was customary to do what was called patenting. Patenting was the heating up of the wire to about 1000°C . By that means the wire was enabled to be drawn with greater ease, and it was possible to obtain higher strains. The effect of patenting was to destroy the fine crystallisation and to substitute a coarse crystallisation. It had occurred to him in connection with Dr. Carpenter's investigations that there was a possible alternative to patenting for the production of high strain wire, and it might be possible to produce those large grains by a low temperature treatment instead of by a high temperature treatment.

Professor C. A. EDWARDS (Swansea) said Professor Carpenter and Miss Elam's work was of great practical significance. In certain circumstances in the manufacture of thin plate steel, particularly where it was necessary for the plates to be subsequently stamped, the con-

ditions were such that phenomenally large crystals might be produced. When those crystals which were very largely confined to the surface of the plate were subjected to any kind of deformation they gave well-defined corrugations in the article such as were illustrated in some of the test-pieces shown by Professor Carpenter. As a result of that he (Professor Edwards) had been almost unwillingly compelled to take up the study of the conditions under which that particular kind of crystallisation occurred in practice, and in that connection the work of Professor Carpenter and Miss Elam was of inestimable value. Only a week ago Mr. Pfeil and he had made iron crystals which were from 2 inches to 3 inches long. (Crystals of this kind were exhibited at the meeting.)

With ordinary mild steel he thought it would be impossible to make very large crystals, and with armco iron it was extremely difficult if not impossible. With mild steel which had been decarburised, however, the conditions were much more favourable, and since a certain amount of surface decarburisation was almost unavoidable during hot rolling, the coarse crystallisation which might then recur might lead to difficulties when the material was subsequently treated. The difficulty was to produce on a laboratory scale a material which was virtually free from carbon. There were many possibilities in that direction, but he would like to say that Mr. Pfeil and himself had found that the best method, or the most convenient method of doing it, was to decarburise in an atmosphere of hydrogen. With that method they got a remarkably good surface without any risks of oxidation. Thus they obtained a material containing no carbon, and therefore no barriers to prevent the crystal growth.

Miss ELAM (London) said Professor Carpenter and she were aware of the work which had been done on zinc. Although the crystal structure was different, the results obtained with aluminium could be applied more or less to other metals.

Colonel Belaiew had referred to the slipping on octahedral planes. It was a very difficult question, but certainly all the experiments carried out at Cambridge with Mr. G. I. Taylor showed that slipping occurred on two planes. It started on one plane, and the crystal axis changed with regard to the axis of the test-piece until two octahedral planes made equal angles with the axis. As soon as the planes made a particular angle—about 61 degrees—with the axis, slipping could take place, as one would expect, on either plane equally well, and in fact it did take place on both, and after that point was reached the crystal axis did not change its position with regard to the test-piece, but remained more or less stationary.

With regard to Professor Benedicks' paper on slipping and twinning, mentioned by Colonel Belaiew, she did not agree that twinning was due to the presence of impurities, because even very pure tin twinned. She had got very large crystals in tin which showed very

beautiful twinning planes, similar to the slip planes in aluminium. They were the same throughout the crystal.

She had been very much interested in Dr. Edwards' iron crystals, and had also been trying some experiments with iron, but had had great difficulty in getting suitable material. She had succeeded in getting some very fair crystals, not so large as Professor Edwards' because they were in very rough sheet, but she hoped that with better materials she might succeed in getting better results.

Professor CARPENTER, in a written reply, referred to Miss Elam's remarks, which dealt with some of the important points raised. He was greatly indebted to Dr. Desch for his account of Polanyi's work, which was of much value and interest. He was very glad that Dr. Hatfield had emphasised the fact that, with the experimental material now available, it could definitely be stated that metallic crystals had such and such properties. As Dr. Desch said, the properties of a metal consisting of the usual mass of small crystals were due in part to the properties of the crystals themselves and in part to those of the boundaries, and it had hitherto been impossible to separate those two factors. Such a limitation no longer existed. He hoped that before long Miss Elam and he would be publishing a paper dealing with the determination of certain other properties of single aluminium crystals. Hitherto, their published work dealt only with tensile tests. They had, however, been accumulating data on the primitive limit of proportionality under tensile stress, Young's modulus of elasticity and fatigue limits. They did not consider that their work threw any fresh light on the nature of the crystal boundary, and that was why he had said nothing about it in the paper. What he did consider was, that the remarkable growth they were able to produce in aluminium crystals was not connected with "amorphous" layers conceived by Sir George Beilby to be produced in plastic deformation. They had found that if their aluminium were stretched in tension to the critical extent and then heated to 350°C .—that temperature being sufficiently high to cause the recrystallisation of any "amorphous" layers—and then subsequently heated at 550°C ., the large crystals could be obtained. That seemed conclusive that the production of the large crystals was not related to "amorphous" layers produced in plastic deformation.

He was much interested in Colonel Belaiew's contribution and his analysis of the various ways in which slip could occur. His speculations fitted in well with their experimental results. The degree of purity of the materials used had a great deal to do with the success or otherwise of experiments designed to produce large crystals. Colonel Belaiew had emphasised the purity of the aluminium. Their metal was not particularly pure ($99\cdot6$ per cent.). As a matter of fact, Dr. Gwyer had a standing order from him to supply him with any purer aluminium that he could prepare, because he felt convinced that the purer the metal the easier it would be to grow large crystals.

Up to the present, however, the above figure represented the best commercial practice that had been reached.

He was glad that Mr. Saniter thought the work had a bearing on the practice of drawing hard steel wire, and he agreed that experiments might well be undertaken on the lines he suggested. Miss Elam and he had been working for some time to produce large iron crystals, and had achieved a certain measure of success, but Professor Edwards, owing to his successful decarburisation of mild steel, had prepared a more suitable material than they had, and had achieved more success. He congratulated him on the splendid crystals he had shown at the meeting. He agreed with Miss Elam, that the occurrence of twinning, contrary to what Professor Benedicks suggested, was not due to impurities in metals. Tin was a metal which could be prepared in a very high state of purity, and there was no difficulty in producing twin crystals in such metal.

Iron and Steel Institute.

THE CORRELATION OF THE CHEMICAL CONSTITUTIONS OF "TRUE STEELS" WITH THEIR MICROGRAPHIC STRUCTURES.

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INTRODUCTION.

BEFORE dealing in some detail with the subject specified in the title, it is advisable briefly to answer the question—What are true steels? There are at present known to scientific metallurgy four true steels: 1. True iron steel. 2. True vanadium steel. 3. True tungsten steel. 4. True ferro-molybdenum steel.

GENERAL DEFINITION.

True steels may be defined as "saturated steels"—that is to say, steels containing neither structurally free iron nor structurally free metallic carbides.

TRUE IRON STEEL.

True iron steel consists entirely of allotrimorphic crystals of the compound micro-constituent "iron pearlite," discovered by the late Dr. H. C. Sorby, F.R.S., about 1863. Pearlite, when properly hardened, is transformed into Sorby's structureless single micro-constituent "iron hardenite," empirically Fe_{24}C .¹ In the early 'sixties the only steel known contained (practically speaking) only the elements iron and carbon; hence Sorby's pioneer discoveries were all made upon this "plain carbon steel." An attempted chemical correlation with Sorby's micrographic work gave only puzzling and unsatisfactory results from a quantitative point of view, and hence he had to make an effort to determine

¹ A solid solution of 13.29 per cent. of Fe_3C in 86.71 per cent. of iron, by which pearlite is easily drilled, turned in a lathe, or cut by a chisel. Iron hardenite also scratches quartz.

the chemical composition of pearlite by the aid of the microscope alone. This method is now recognised to be quite misleading, and it led Sorby to suggest provisionally that pearlite was built up of alternating layers of a hard carbide of iron alternating with soft pure iron laminae which were about twice as wide as the carbide striæ. He therefore tentatively concluded that pearlite contained about two-thirds of pure iron mechanically mixed with about one-third of carbide of iron. When Sorby, in 1885 and 1886, read papers on the micrographic analysis of steel before the Iron and Steel Institute, he was obviously unaware of the research work of Sir Frederick Abel, F.R.S., read in 1885 before the Institution of Mechanical Engineers. Abel and Deering had conclusively proved that in "blister steel" containing about 1 per cent. of carbon the latter existed (in the unhardened steel) nearly wholly as the definite compound Fe_3C . Curiously enough, Abel himself was evidently unacquainted with the micrographic work on steel of Dr. Sorby. Unfortunately, this lack of correlation of the work of scientific men working upon the same subject by different methods is still common.

In the early 'nineties the author, by strictly correlative researches and by chemical, micrographic, and thermal methods, determined the quantitative chemical composition of iron pearlite, proving it to consist constitutionally of a mechanical mixture of alternating striæ of pure iron 86·71 per cent., and carbide of iron (Fe_3C) 13·29 per cent. Empirically this composition corresponds with pure iron, 99·11 per cent. + 0·89 per cent. carbon.¹ The mass microstructure of pure pearlite therefore consists entirely of juxtaposed allotrimorphic (octahedral) crystals, containing, in a state of mechanical mixture with pure iron, about 13·3 per cent. of carbide of iron striæ containing about 6·7 per cent. of carbon. With the above chemical constitution there is always associated 100 per cent. of pearlite *or true iron steel*, the crystals of which (especially when annealed) present under the microscope (say at 50 diameters) a beautiful display of colours, the fine carbide striæ acting like an interference grating. Sorby indeed, before using powers sufficiently high to resolve the Fe_3C striæ, deduced their existence from these colours.

Further, in connection with true iron steel (= pearlite 100 per

¹ *Proceedings of the Institution of Civil Engineers*, December 1895.

cent.), the author discovered that Osmond's critical thermal points Ac1 and Ar1 coincided with the maximum absorption and evolution of heat respectively on heating and cooling; but that with carbon either above or below 0.89 a diminution of heat was registered, owing to the dilution of the pearlite with structurally free Fe_3C (cementite), or with structurally free iron (ferrite), giving respectively "supersaturated" or "unsaturated" steels. True or saturated iron steel may be conveniently here defined thirdly as a "dyad steel," since it contains only the two elements iron and carbon. Concerning this true steel (and, indeed, the other three true steels about to be described) it may be truly said, as the blood is the life, so is the carbon the steel.

TRUE VANADIUM STEEL.

The general influence of the then rare element vanadium on steels was determined by the author in a series of researches made in Sheffield University during the years 1899 to 1902. The discovery of the existence of true vanadium and other true steels was, however, made possible by the development (from 1892 and onwards) by the author and Dr. A. A. Read, Professor of Metallurgy in the University of Wales, of the differential electrolytic method for carbon analysis first used in a crude form by Binks and Weyl for the estimation of carbon in pig iron. A scale drawing of the apparatus found to be most efficient was published in the *Proceedings of the Institution of Mechanical Engineers* for March 20, 1914. It consists of two beakers charged with an electrolyte of distilled water and HCl having a specific gravity of 1.02. The polished steel bars, about 3 inches long and $\frac{3}{8}$ inch in diameter, suspended in the dilute acid to a depth of about 2 inches, constituted the anodes, whilst cathodes of platinum plates enclosed in porous cells were employed. The current was from storage cells, and by means of an ammeter and a resistance frame a current density between 0.50 and 0.55 ampere per square millimetre of anode, with a voltage at the terminals between 0.8 and 1.6, was registered during a twelve-hour electrolysis of the vanadium steels. These yielded for chemical analysis about half a gramme of the carbide or mixed

carbides. These analyses proved, *inter alia*, that iron containing, say, 0.9 per cent. of carbon and a little over 2.3 per cent. of vanadium yielded a mechanical mixture of the carbides of iron and vanadium with the formula $2\text{Fe}_3\text{C} + \text{V}_4\text{C}_3$. When, however, about 4.8 per cent. of vanadium was present, Fe_3C was practically absent, and only the single carbide V_4C_3 was found. It was also established that this result was constant with further additions of vanadium to the steels, at any rate up to 13.5 per cent. vanadium. Hence iron containing, say, 4.75 per cent. vanadium constitutes vanadium pearlite or true vanadium steel, the constitutional formula of which is $\text{Fe}_{72} + \text{V}_4\text{C}_3$. Vanadium pearlite etches dark brown, its carbide being in that very fine state of division which has been called "troostitic," to distinguish it from the laminar carbide of iron pearlite. The latter transforms to its hardenite at 730°C ., whereas vanadium pearlite requires a temperature of not less than 1400°C . to determine the solution of its troostitic carbide in the iron containing it, and the vanadium hardenite when fixed by quenching in cold water micrographically resembles iron hardenite, but is considerably harder, readily scratching topaz, and possibly corundum. True vanadium steel may be chemically distinguished from true iron steel (which is a dyad substance containing only iron and carbon) as a *triad* steel, consisting of iron, vanadium, and carbon.

TRUE TUNGSTEN STEEL.

In true tungsten steel there is a displacement point of all Fe_3C when the tungsten reaches a little above 11 per cent. and the carbide (WC) is formed. If a little less than 0.75 per cent. of carbon is present, it is entirely appropriated by the tungsten. Should the added tungsten be well under 11 per cent., the mixed carbides ($x\text{Fe}_3\text{C} + y\text{WC}$) are obtained. If, on the other hand, the tungsten present distinctly exceeds 11 per cent., a tungstide of iron (Fe_2W) is formed. Tungsten pearlite ($\text{Fe}_{26} + \text{WC}$) is a triad substance containing the three elements, iron, tungsten, and carbon. Its transformation range seems to begin about 850° , and is complete between 1100° and 1200°C . The resulting tungsten hardenite corresponds with the formula (Fe_{26}WC), which micrographically resembles iron

hardenite (Fe_{24}C) and readily scratches quartz. To transform completely tungsten hardenite back to its pearlite it requires heating up to a yellow heat (near 1100°C.), and then to be slowly cooled down overnight to atmospheric temperature. Tungsten pearlite micrographically presents its carbide in a fine state of division (sorbitic), which never laminates like Fe_3C .

TRUE FERRO-MOLYBDENUM STEEL.

The critical displacement point for the above triad true steel is at about 18.2 per cent. of molybdenum with, say, about 0.75 per cent. of carbon. Near these critical chemical points Fe_3C vanishes, being entirely replaced by a most remarkable ferro-molybdenum double carbide true steel, which persists up to at least 21 per cent. of molybdenum. Ferro-molybdenum carbide is practically *non-magnetic*, and its formula in its lowest terms corresponds to $\text{Fe}_3\text{Mo}_3\text{C}$. More probably its formula may be $\text{Fe}_6\text{Mo}_6\text{C}_2$. Its pearlite and hardenite considerably resemble those of tungsten. The formula of ferro-molybdenum pearlite is $\text{Fe}_{24} + \text{Fe}_3\text{Mo}_3\text{C}$, and its hardenite corresponds with $(\text{Fe}_{24}\text{Fe}_3\text{Mo}_3\text{C})$. The microstructures of both these constituents resemble those of tungsten true steel, with which their hardnesses seem identical. Ferro-molybdenum carbide seems to be chemically the most stable of the carbides of steel, and it is little affected by big differences in the acid strength of the electrolyte employed, or by the density of current used for electrolysis.

TABULATED DATA (APPROXIMATE).

Names of True Steels.	Carbon Saturation ¹ Points. Per Cent.	Pearlite Formulae of Saturated Steels.	Compositions of Saturated Steels. Per Cent.	Empirical Composition of Hardenites.	Displacement Points of Fe_3C . Per Cent.
Iron . . .	0.89	$21\text{Fe} + \text{Fe}_3\text{C}$	$\text{Fe } 87 + 13$	Fe_{24}C	...
Vanadium . .	0.83	$72\text{Fe} + \text{V}_4\text{C}_3$	$\text{Fe } 94.5 + \text{V}_4\text{C}_3 \text{ } 5.5$	$\text{Fe } 72 \text{ V}_4\text{C}$	4.8 V
Tungsten . .	0.72	$26\text{Fe} + \text{WC}$	$\text{Fe } 88 + \text{WC } 12$	Fe_{26}WC	11.3 W
Ferro-molybdenum	0.71	$24\text{Fe} + \text{Fe}_3\text{Mo}_3\text{C}$	$\text{Fe } 70.5 + \text{Fe}_3\text{Mo}_3\text{C } 29.5$	$\text{Fe}_{24}\text{Fe}_3\text{Mo}_3\text{C}$	18.3 Mo

¹ "Eutectoid," as re-named by the late Professor Howe of Columbia University, America.

ADDENDUM.

ELEMENTS WHICH FAIL TO FORM TRUE STEELS.

Employing up to 24 per cent. of the added elements, the author could find no evidence of the production of true steels by the metals chromium, cobalt, manganese, or nickel.

Chromium.

No evidence of a true chromium steel was obtained. Chromium steels when electrolysed revealed the presence of Moissan's two carbides, Cr_3C_2 and Cr_4C , and also, when from 15 to 24 per cent. of chromium was present, a double carbide of the formula $(2\text{Fe}_3\text{C}, 3\text{Cr}_4\text{C})$ was isolated. At about 14 per cent. chromium there was found a critical corrosion point from which (up to 24 per cent. of chromium) the resultant residue was nearly twice that obtained from steels containing about 1 to 10 per cent. of chromium.¹ During the last few years this 14 per cent. chromium alloy has become familiar in the form of "stainless steel."

Cobalt.

No evidence of a true cobalt steel was obtained from a set of alloys containing from about 2.5 to 21 per cent. of cobalt and 0.8 per cent. carbon. The dry electrolytic residue (in every experiment) contained only about $5\frac{1}{2}$ per cent. of the total cobalt in the form of Co_3C . Evidence, however, was obtained that about another $5\frac{1}{2}$ per cent. of the total cobalt existed in solid solution as a cobaltic hardenite which decomposed on electrolysis.

Manganese.

In alloys containing about 0.9 per cent. of carbon, with manganese ranging from 0.5 to 15 per cent., no evidence of a true manganese steel could be found. At 20 per cent. manganese the electrolytic method broke down, owing to secondary internal galvanic action, which caused the 20 per cent. manganese alloy residue to register about 20 per cent. of carbon.

¹ See *Journal of the Iron and Steel Institute*, 1911, No. I.

Broadly speaking, as the manganese percentage rose, so the iron displaced by manganese increased; but from 11 to 13.5 per cent. manganese a double carbide of iron and manganese ($3\text{Fe}_3\text{C}$, Mn_3C) was registered. In the absence of carbon, the alloys of iron and manganese present remarkable features. For example, iron containing 7.28 per cent. manganese registers a yield point and a maximum stress of 45.8 tons per square inch and no elongation. An alloy with 13.38 per cent. manganese has a yield point of 23.6 tons per square inch, a maximum stress of 39.1 tons, and 2.5 per cent. of elongation. This alloy has a faint yellow colour. Iron alloyed with 30.6 per cent. manganese has the colour of pale brass, a yield point of 19.7, and a maximum stress of 41.6 tons. The elongation on 2 inches is 58 per cent., and the reduction of area 65.1 per cent. The above remarkable facts observed by the author and Mr. F. K. Knowles many years ago require careful microscopic correlation.¹

Nickel.

From a set of nickel steels containing from 3.3 to 98.4 per cent. nickel no indication of a true nickel steel was noted. The carbon in these alloys varied from 0.53 to 0.88 per cent. The commercially pure nickel bar (98.4 per cent. nickel) contained 0.38 per cent. of carbon. Neither was any evidence obtained of the existence of a double carbide of iron and nickel. Throughout the electrolyses mixtures of Fe_3C and Ni_3C were isolated. With 3.3 per cent. nickel the mixed carbides corresponded with the formula ($31\text{Fe}_3\text{C} + \text{Ni}_3\text{C}$). From a steel containing 20.3 per cent. nickel the mixture of carbides separated = $\text{Fe}_3\text{C} + 35\text{Ni}_3\text{C}$.

¹ During the discussion of the present author's paper on "The Influence of Carbon on Iron," read in December 1895 before the Institution of Civil Engineers, Mr. (now Sir Robert) Hadfield called attention to the fact that an iron alloy he had just prepared containing under 0.1 per cent. of carbon and about 3.5 per cent. of manganese was quite soft; whilst an iron alloy with 3.5 of manganese but 0.54 per cent. of carbon was so hard that it could not be filed or in any way machined. This remarkable discovery was the pioneer observation which led the present author and Mr. Knowles (see *Journal of the Iron and Steel Institute*, No. I., May 1906) to reveal, in the crucible steelworks of Sheffield University, the astounding properties of practically carbon-free alloys of iron and manganese, a few of which are herein re-described as examples. In fact, Hadfield in 1895 had forecast, in the field of mangano-ferrous research, a discovery which was destined later to establish a metallurgical paradox of astounding importance, the nature of which even to the present day (1923) lacks any satisfactory explanation.

The bar of metallic nickel yielded no Fe_3C , but only Ni_3C , and free carbon due to the internal electrolytic decomposition of a considerable amount of Ni_3C . Carbide of nickel does not seem to form a pearlite but only a hardenite, which is electro-positive to Fe_3C , depositing free carbon. In the absence of carbon, iron and nickel form the definite alloy Fe_7Ni containing 13 per cent. nickel. This unique alloy is relatively little responsive to the operations of hardening or annealing. In its normal condition this *nickelide of iron* has a maximum tensile test of about 90 tons per square inch associated with a reduction of area of 46 per cent.

DISCUSSION.

Sir ROBERT HADFIELD, Bart., F.R.S., Past-President, said the paper by Professor Arnold would remind members of a great deal of work done in the past on alloys of iron with special elements. Most of those alloys referred to in the paper were now current production, that is to say, they were on the market in the ordinary way. Many of the mysteries relating to them in the past were now no longer mysteries, thanks to the great work done by the Iron and Steel Institute, of which he thought they had every reason to be proud, as it had indeed led the way in developments of that kind.

Professor Arnold had referred to the question of the peculiar properties of the lower or brittle percentage of alloys of iron and manganese, first produced in connection with the speaker's researches as regards the discovery of manganese steel more than thirty years ago. The facts to which he referred were quite correct; that was, a comparatively slight difference in the percentage of carbon would turn the brittle $3\frac{1}{2}$ to 3 per cent. manganese iron into quite a different material. Nevertheless, he did not think any particular commercial use had been found for an alloy of iron and manganese of that particular nature. "Manganese steel" still held its own in the sense of possessing the extraordinary quality of becoming hardened by pressure. Its use therefore continued, and no doubt would continue to be very widespread. Professor Arnold had referred to the paper communicated in 1911. He thought that all who were studying corrosion (and who, indeed, was not studying corrosion?) would agree how wonderful was the amount of progress which had been made. That paper was of very great importance, and very useful information was contained in the joint experiments of Professors Arnold and Read, as indicated in Table V. Dr. Arnold had reminded him of the fact—and perhaps Dr. Hatfield would express an opinion on the point—that he had stated distinctly in Table V. that after the chromium rose beyond 12 to $12\frac{1}{2}$ per cent.—(Dr. ARNOLD: 14 per cent.)—the rate of corrosion tended rapidly to diminish. That was a very important fact, as showing that those higher percentages would repay careful examination. The Institution of Civil Engineers had a very important research in hand in respect of a large number of specimens which had been examined for corrosion in sea water and fresh water in various parts of the world. That research would, of course, take a long time to complete; but he had seen a few of the preliminary reports. There were no very definite results so far, and he did not think he was giving away any secrets of the Committee, or that the Chairman would object to his stating that although eighteen months' work had been done it was still not possible to draw from the experiments any definite conclusions which

would enable them to solve that very perplexing subject in relation to the great problem of corrosion. He was not, of course, here referring to special applications, such as rustless and stainless steel, the employment of which for various purposes was now current with great advantage.

Dr. W. H. HATFIELD (Sheffield) said the paper embodied the result of Dr. Arnold's life study of the constitution of steel. Dr. Arnold spoke of true steel, and, of course, they all understood what he meant. Dr. Arnold was a distinguished metallurgist, and it was he who first of all determined the fact that if the carbon content in a pure steel were increased to 0.89 per cent., the eutectoid composition was reached. That was a very important discovery and had had extremely valuable results. Dr. Arnold had further discovered that if carbon were added above 0.89 per cent., the constituent cementite appeared, together with the excess carbon.

In his opinion one of the most interesting contributions Dr. Arnold had made was that which referred to his "true" or eutectoid vanadium steel, in which he showed that with certain conditions of concentration and composition, if 4.75 per cent. of vanadium was present, the whole of the carbon was in combination with the vanadium, giving vanadium carbide and iron. He was not quite clear whether some of the vanadium might not be in solution in the iron.

Dr. ARNOLD said there might be a trace.

Dr. HATFIELD, continuing, said it was of interest to know that such high temperatures as 1400° C. had to be attained before that carbide went into solution. On p. 218 Professor Arnold said that during the last few years the 14 per cent. chromium steel had become familiar in the form of stainless steel. He ventured to take exception to that statement, for the simple reason that Professor Arnold's alloys were made from ferro-chromium of a necessarily high carbon content. The 14 per cent. chromium alloys which Dr. Arnold and Sir Robert Hadfield had experimented with had such a high carbon content that they were not stainless, and it was really left to Brearley in later years to discover true stainless steel. Nevertheless, it was proper to admit that the work which Dr. Arnold and Sir Robert Hadfield conducted years ago laid a strong foundation for the general knowledge of chromium steel subsequently attained.

The carbon, manganese, and iron alloys which Sir Robert Hadfield discovered some thirty years ago, with their well-known characteristics such as high tensile properties, non-magnetic properties, and wear resistance, were of great interest, and it was interesting likewise to compare them with the pure iron manganese series which Professor Arnold and Mr. Knowles investigated years ago in a paper which would well repay perusal.

Dr. F. C. THOMPSON (Manchester) said that during the time he had held the Sorby Fellowship he was working on the etching properties of the actual series of steels that Professor Arnold had used for his carbide determinations. What he had been attempting to do was to differentiate, by etching tests, between the different carbides, &c., which were present. That work had to be discontinued before it had reached a publishable state, but there were two series of steels, the tungsten series and the cobalt series, which had been completed. From the etching properties of the constituents in those two series of steels, evidence could be deduced that the conclusions which Dr. Arnold had reached with regard to the constitution of these steels were correct. Especially with regard to tungsten series was it possible to differentiate by etching tests each of the constituents which Dr. Arnold had discovered. In those two series the chemical work of Dr. Arnold had been completely substantiated. Therefore, although he (Dr. Thompson) had embarked on his work with a certain amount of reservation in regard to those conclusions, he was now glad to admit to the Institute and to Professor Arnold that the net result of the etching tests had been completely to substantiate the views which Professor Arnold had propounded.

Colonel N. T. BELAIEW, C.B. (London), said an extremely important point in the researches of Dr. Arnold and his pupils was that the data they arrived at had been based on strictly co-relative researches, by chemical and micrographic methods. The late Professor Tschernoff had always attached much importance to the results which Professor Arnold and his pupils and colleagues were obtaining from their microstructures. Such results could only be taken into consideration and used when they were correlated by chemical researches and mechanical tests, and in order to illustrate such co-ordinated work Professor Tschernoff always used to refer to such researches as "the work of Professor Arnold." The series of papers published by Dr. Arnold in collaboration with Professor Read and others were the kind of research work which Professor Tschernoff recommended to their attention, and the importance of the chemical investigations on carbides was one of the ideas which became ingrained in his pupils.

Dr. Arnold pointed out that apparently Dr. Sorby was unaware of some of the chemical experiments which Abel carried out. When Professor Tschernoff drew the attention of his pupils to the importance of those chemical investigations they became so interested in that particular field of research that they tried to find out what had actually been done in that field, and he (Colonel Belaiew) had been able to ascertain that between 1785 and 1787 on both sides of the Channel, in France and in England, very important researches were carried through with reference to the determination of carbides in steel. He would like to take that opportunity of coupling the name of Guiton de Morveau with that of Dr. Priestley who, working in Birmingham, was

able to show that there was about 7 per cent. of carbides of iron in the Birmingham nails; he made a series of experiments, and his analyses were extremely important, because if they took 7 or 8 per cent. of carbide, that would bring them to about 0.5 per cent. of carbon in those Birmingham nails; so that even in the eighteenth century the importance of that analysis was realised, although it took about one hundred years to again emphasise what had apparently been entirely forgotten during that time.

Professor ARNOLD, in reply, sincerely thanked the members for their sympathetic attitude and kind criticisms of his paper. He could only admire the ingenuous courage of his old student, Professor F. C. Thompson, in publicly admitting that at one time he was somewhat rather doubtful of the accuracy of his (Professor Arnold's) conclusions on the chemistry of the carbides, but that after further investigation he now candidly confirmed the work and conclusions of Professor Read and himself. In reply to another old student, Dr. Hatfield, he thought the latter, on further consideration of the tabulated results presented from time to time to the Iron and Steel Institute and the Institution of Mechanical Engineers, would see that the critical corrosion point was near 14 per cent. of chromium where a sudden resistance to corrosion from an observed range of from 14 to upwards of 20 per cent. was observed, and was so great that the weights of the carbide residues were just about twice the quantities obtained from steels containing chromium below 14 per cent.

In conclusion he greatly appreciated the contribution of Colonel N. T. Belaiew and his revelation of the approval of Professor Tschernoff of his (Professor Arnold's) work. The appreciation of the great (but, alas, now deceased) Russian metallurgist was to him (Professor Arnold) an asset of enduring value.

Iron and Steel Institute.

ECONOMIC PRINCIPLES GOVERNING THE USE OF ELECTRICAL POWER IN IRON AND STEEL WORKS.

By C. A. ABLETT, M.Inst.C.E. (LONDON).

THE governing consideration affecting the installation of plant in a steelworks, as in any other works, is the return on the capital expended, and this principle applies as much to power plants as to engines or motors driving mills, or to the mills themselves. This paper is principally concerned with the selection of power plant, and presupposes that the directors' policy has already been decided in so far as the products of the works are concerned. In deciding on the products of the works the directors will have considered the market in which it is proposed to compete, and will have taken into account every aspect of the case; in the selection of a power plant a chain of reasoning on the same general lines has to be gone through if economical results are to be obtained.

The source of power supply can be considered under four headings :

I. Power produced by the works themselves from natural resources available within the works.

II. Power produced by the works themselves from exhaust steam.

III. Power produced by the works themselves from fuel used for that purpose.

IV. Power purchased from an outside source.

I. POWER PRODUCED BY THE WORKS THEMSELVES FROM NATURAL RESOURCES AVAILABLE WITHIN THE WORKS.

Natural resources resolve themselves under the following heads :

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- (a) High load factor.
- (b) Blast-furnace or coke-oven gas.
- (c) Hot burnt gases from steel furnaces, puddling furnaces, &c.
- (d) Other heat resources, such as hot slag.

(a) High Load Factor.

In the above list high load factor is considered a natural resource of a steel or iron works, as its effect is to cheapen the cost of power produced by a steel or iron works by reducing the capital charge, which forms part of the total cost per unit of power (kilowatt-hour) produced, just in the same way as the utilisation of a natural heat resource reduces the fuel charge, which also enters into the total cost per unit (kilowatt-hour) of power produced. Where the load factor is high the power generating plant is being used to better advantage than where the load factor is low, as a greater number of units of power are being generated from a plant of definite capacity during the course of the year, and as the annual capital charges, which are constant for a definite capacity of plant, are divided by a large number of units of power produced the capital cost per unit of power is naturally less than if they were divided by a smaller number of units.

Experience has proved that the load factor of an iron or steel works can easily be between 60 and 70 per cent., and in some cases even higher, and as the importance of load factor is realised means can often be devised for improving it. Published records show that the average load factor of the municipal electrical supply of five of the largest industrial cities in Great Britain was, over a recent period of twelve months, 21·48 per cent.

It will thus be seen that on these figures an iron or steel works produces about three times as many units of power from their plant as a public supply authority would, and consequently the capital charge per unit of power produced would, in the case of an iron or steel works, be about one-third that in the case of a public supply authority.

Where the natural heat resources are used as a source of power the capital charges form a larger proportion of the cost of generating power than where coal is burnt, so the advantages of high load factor become magnified. The following examples show the effect

of high load factor in cheapening the cost of power. A steam-turbine plant with gas-fired boilers is assumed.

Cost of Power with Steam-Turbine Plant and Gas-fired Boilers.	65 per Cent. Load Factor. Cost Pence per Unit.	21·5 per Cent. Load Factor. Cost Pence per Unit.
Capital charges	0·14	0·41
Water, oil, stores	0·02	0·04
Wages	0·02	0·05
Repairs, cleaning, maintenance	0·01	0·04
Management and general establishment charges	0·01	0·03
Total cost ¹	0·20	0·57

It is of interest to compare these costs with those given on p. 234 for steam-turbine plant with coal-fired boilers, from which it will be seen that high load factor has a greater effect in cheapening the cost per unit than saving the coal bill by using a waste heat resource; correspondingly, the advantage of high load factor together with the utilisation of a natural heat resource is an ideal condition. Corresponding figures for slow-speed gas-engine plant are given below.

Cost of Power with Slow-speed Gas-Engine Plant.	65 per Cent. Load Factor. Cost Pence per Unit.	21·5 per Cent. Load Factor. Cost Pence per Unit.
Capital charges	0·19	0·57
Water, oil, stores	0·03	0·05
Wages	0·03	0·06
Repairs, cleaning, maintenance	0·02	0·07
Management and general establishment charges	0·02	0·07
Total cost ¹	0·29	0·82

While the above figures show that the cost of power produced by slow-speed gas-engines exceeds that produced by steam-turbine plant with gas-fired boilers, it frequently happens that there is insufficient gas to produce the whole of the power from steam-turbine plant and gas-fired boilers. In such a case the power plant might consist of a combination of gas-fired boilers and coal-fired

¹ Gas cleaning is included in both the steam-turbine and gas-engine costs.

boilers, in which case the cost of power produced by steam turbines would be a combination of the costs given above and those on p. 234, so that the total cost of power produced by steam-turbine plant at 65 per cent. load factor can easily exceed the cost produced by gas-engine plant.

A comparison of the above cases and those on p. 234 will show that at a 21·5 per cent. load factor the cost of power produced by slow-speed gas-engines is nearly as great as that produced by steam-turbine plant with coal-fired boilers. This shows clearly that the gas-engine is not an economical machine except at high load factors, but this only becomes apparent when the overall economy, including capital charges, &c., is compiled.

The above comparisons and results adduced from them relate to a central electric power-producing plant. If the power-producing plant included either gas-driven blowing-engines or steam turbo-blowers, the above chain of reasoning applied to the combinations will show a marked increase in economy in favour of the gas-driven combination, as the gas-driven blowers will appear in a very favourable light as compared with the steam turbo-blowers.

In general, the more economical the power plant is in fuel consumption, the greater the capital cost of the plant becomes. Such special expenditure would therefore not generally be undertaken, except under high load factor conditions. This point is well illustrated if the cost of production with steam-turbine plant and coal-fired boilers at 21·5 per cent. load factor given on p. 234 be compared with the cost of production with gas-engine plant at a 65 per cent. load factor given on p. 227. In the case of the steam-turbine plant with coal-fired boilers the capital charge per unit is 0·36, while in the second case the more expensive but more economical slow-speed gas-engine plant shows a capital charge per unit of 0·19.

By capital charges is meant the interest on the capital expended, the annual allowance for depreciation of plant, and the annual allowance for obsolescence of plant ; this last charge being made to provide against the contingency of the plant becoming obsolete before it is worn out. Experience has shown that the combined figure for depreciation and obsolescence taken over whole works averages out to about 5 per cent. per annum ; but if this combined figure be applied to individual items of plant in order to arrive at

the cost of production incorrect conclusions can easily be arrived at, and it is therefore preferable in dealing with individual items of plant to assess the depreciation and the obsolescence separately.

(b) *Blast-Furnace or Coke-Oven Gas.*

On considering the use of blast-furnace or coke-oven gas as a possible source of electric power, full consideration must be given to the fact that it is more economical to use these gases for heating furnaces than as a source of power, and therefore the gases should be used for heating to the fullest possible extent, and the residue left over, after all heating requirements have been fulfilled, should then be used for the production of power.

In using the residue of gas for the production of power one has the choice of burning it under boilers for steam plant, or of utilising it in gas-engines. In comparing these two methods, taking all working and capital charges into account, one factor will be found to be the relative capital costs of steam and gas plant; another factor, the proportion the residue of gas bears to the power requirements, including load factor of the works, keeping clearly in mind that where a commodity is available means will be found to utilise it profitably; in other words, surplus gas should not be employed uneconomically, because there is no immediate prospect for its use in view.

A third factor will be the question of obsolescence, for one must look well into the future in comparing the economic advantages of two methods, considering that a decision regarding the installation of steam or gas plant may bind the works to a definite policy for some such period as twenty years, and therefore the question of the possible obsolescence of the method chosen for the production of power within a period of twenty years comes into view, and with it the capital charges to be made to provide for the contingency that the plant may become obsolete before it is worn out.

Modern steam plant utilises about 15 per cent. of the heat supplied to it to produce power, the remainder is wasted. Modern gas-engine plant utilises about 30 per cent. of the heat supplied to it to produce power, and of the remainder only a small portion is recoverable and the greater part wasted. Means will most probably be found in the future for utilising more or less completely the heat which, under present conditions, would be wasted; thus

the less efficient steam plant will become obsolete before the relatively more efficient gas plant, and so it may be argued that steam plant should carry higher obsolescence charges than gas plant.

In dealing with the question of obsolescence, it may be pointed out that the buildings for housing plant may easily become obsolete at the same time as the plant which they house, and should be designed with this in view. There are many cases where the buildings, after the removal of the plant, stand vacant. The capital invested in such buildings is earning no income—in fact, the buildings are expensive obstructions. On considering the question of obsolescence one must endeavour to look into the future to determine in what direction technical improvements may be expected which are likely to render existing plant obsolete, and in doing this consideration must be given to the possibility of power-producing plant which will prove less wasteful in heat than those which are available to-day.

The extent to which a gas-engine plant, a steam plant, or any other form of heat engine can utilise the heat supplied to it is governed by the limits of temperature within which it works. While the combustion of gases in a gas-engine cylinder take place at a very high temperature, gas-engines exhaust the burnt products of combustion also at a relatively high temperature, and if means become available to enable the products of combustion to be exhausted at or about atmospheric temperature, thus materially increasing the temperature range in which the gas-engine works, the gas-engine plant would utilise considerably more than 30 per cent. of the heat supplied to it. Boilers have been connected to gas-engine exhausts with the object of achieving this result, but it is not impossible that a materially better solution of this problem may become available. Steam-turbine plants working at abnormally high pressures have been introduced, with the object of increasing the temperature limits to enable the steam plant to utilise more than 15 per cent. of the heat supplied to it. Apart from superheat, comparatively small increases in steam temperatures beyond the present normal limits involve very great increases in steam pressures. By adopting such abnormal pressures a saving of the order of 15 per cent. on the coal bill becomes possible.

Referring to the costs on p. 234, such a saving at a 65 per

cent. load factor would reduce the cost per unit from 0·42 to 0·39, effecting a saving of 7·1 per cent. in the cost of power. At 21·5 per cent. load factor the possible saving to be effected by this means would be 5·8 per cent. in the cost of power. In adopting such abnormally high pressures great care is necessary that the extra capital cost involved does not give rise to increased capital charges per unit produced, which will completely overshadow the saving in the coal bill. This is more likely to happen at a low load factor than at a high one.

It should be pointed out that if either gas-engine plants or steam-turbine plants could be arranged to exhaust at a temperature greatly below atmospheric temperature a very great increase in the extent to which heat is utilised would be attained, but at present it is difficult to see what practical means could be adopted to enable such machines to exhaust at such low temperatures.

On considering steam plant from the economic aspect the overall performance of the boilers, the steam-engines and turbines, and all auxiliary plant in the power station must be considered, and this naturally applies to plant working at abnormally high pressures. If one portion of the plant only is considered—for example, the steam consumption of a steam turbine—the result obtained will probably be misleading, and in this connection it is to be regretted that comparatively few performance figures for steam boiler plants are published in comparison with those published for steam-turbine plants.

(c) *Hot Burnt Gases from Steel Furnaces, Puddling Furnaces, &c.*

As these gases do not, or should not, contain any combustible material they can only be used, as far as power production is concerned, to raise steam under boilers. Hot gases from nearly all puddling furnaces are being used to raise steam, and where this is being done economically it is found that sufficient power can be produced to drive the rolling-mills and other plant in an ironworks without recourse to any other source of supply, except in cases where considerable quantities of steel are being rolled in the mills in addition to iron.

The application of hot gases from steel furnaces to raise steam was originally described by Mr. T. B. Mackenzie in a paper read

before the Institution of Engineers and Shipbuilders in Scotland in 1912, and since then a number of boilers have been installed in conjunction with steel furnaces, so that it has been demonstrated that this method of raising steam is quite practical; but it must be remembered that the quantities of steam which can be raised in this way is very strictly limited and can only supply a portion of the power requirements of a steelworks. It should be pointed out that the application of boilers designed for coal-firing will not prove economical for this purpose. Where hot gases are used the conditions are different, and to obtain good results the boiler flues, &c., must be designed to meet conditions.

(d) Other Heat Resources, such as Hot Slag.

There are other heat resources, such, for instance, as hot slag, which must not be left out of consideration, because possibly no practical means has yet been devised for their utilisation. The author thinks it is not unreasonable to say that the solution of such problems depends on economic pressure.

II. POWER PRODUCED BY THE WORKS THEMSELVES FROM
EXHAUST STEAM.

An exhaust steam turbine is usually installed to work in conjunction with an old steam-engine which has already lost many years of its life and is obsolescent, its capital value presumably having been heavily written down. An exhaust turbine, a new machine, thus directly it is installed automatically becomes obsolete to a similar degree to the steam-engine. The capital expended on the exhaust turbine may therefore be considered to have undergone a heavy depreciation from the moment that it is expended; but it is more usual to allow a much greater annual obsolescence charge on exhaust steam-turbine plant than on other new plant, so that the capital is more quickly redeemed, thus treating the exhaust steam turbine as a stop-gap arrangement. These capital charges should be brought in to any economic comparison which may be made when the economic aspect will assume its true proportions. If, therefore, after considerable capital charges have been allowed for obsolescence, or, in other words, the capital cost of the exhaust steam plant is so arranged

that it would be written off in a comparatively short period and the total costs of the plant then appear favourable, a favourable case has been made out for exhaust steam.

An exhaust steam scheme may easily appear very attractive from the point of view of enabling the available power in the works to be increased at an apparently low capital cost, and it may fulfil that purpose for a few years; but if one looks further into the future, when future extensions to the works may demand additional power, an exhaust steam plant may prove a serious stumbling-block, as it would become a question either of obtaining the additional power at the expense of high operating costs, or of sacrificing the capital expended on the exhaust steam plant before the redemption period is completed. It must be remembered that a combination of an exhaust steam turbine and a single engine, or engines, cannot be separated from the general power problem of the works for individual consideration.

As an exhaust steam turbine tends to perpetuate obsolescent rolling-mill engines, one is not justified in considering exhaust steam as a natural heat resource of a works—in fact, it is an asset of a more than doubtful character. The exhaust steam problem requires care in its consideration also from an engineering aspect, as the performance figures of exhaust turbines are frequently given under much more favourable conditions than are obtainable in practice. While there is an economic field of application for the exhaust steam turbine, this machine unfortunately has been pushed, in the past, into many places which lie outside its economic field of application by exceptionally able salesmanship on the part of the manufacturing firms, and the knowledge of such cases has in recent years brought about a reaction against the exhaust turbine which has tended to restrict its legitimate economic field of application.

III. POWER PRODUCED BY THE WORKS THEMSELVES FROM FUEL USED FOR THAT PURPOSE.

Where a steelworks has no natural heat resource available for the production of power, such as blast-furnace or coke-oven gas or hot burnt gases from furnaces, or has insufficient natural heat resources to produce the total amount of power which they

require, and must therefore purchase fuel for the production of power, they still have the advantage of a natural resource in having a high load factor. High load factor, as is pointed out in Section I. of this paper, has the effect of enabling power to be produced cheaply by reducing that portion of the total cost per unit of power (kilowatt-hour) which is represented by capital charges—for example; assuming a load factor of 65 per cent., which represents the figure easily obtainable in an iron or steel works, the cost of power produced by the works themselves, assuming a coal cost of 20s. per ton and that the plant consists of boilers and high-pressure steam-turbine plant, would be as follows :

<i>Cost of Power with Coal-fired Boilers and Steam-Turbine Plant,</i> 65 per Cent. Load Factor.							Cost Pence per Unit.
Capital charges . . . . .	.	.	.	.	.	.	0·12
Coal . . . . .	.	.	.	.	.	.	0·24
Water, oil, stores . . . . .	.	.	.	.	.	.	0·02
Wages . . . . .	.	.	.	.	.	.	0·02
Repairs, cleaning, maintenance . . . . .	.	.	.	.	.	.	0·01
Management and general establishment . . . . .	.	.	.	.	.	.	0·01
Total cost							0·42

If a load factor of 21·5 per cent. were assumed, which represents the average of five large public supply authorities, the cost would be as follows :

<i>Cost of Power with Coal-fired Boilers and Steam-Turbine Plant,</i> 21·5 per Cent. Load Factor.							Cost Pence per Unit.
Capital charges . . . . .	.	.	.	.	.	.	0·36
Coal . . . . .	.	.	.	.	.	.	0·34
Water, oil, stores . . . . .	.	.	.	.	.	.	0·03
Wages . . . . .	.	.	.	.	.	.	0·05
Repairs, cleaning, maintenance . . . . .	.	.	.	.	.	.	0·05
Management and general establishment . . . . .	.	.	.	.	.	.	0·03
Total cost							0·86

The value of high load factor as a natural resource has been appreciated by those who advocate “linking up.”

The capital cost per kilowatt installed of a power plant installed in an iron or steel works will be materially less than that of a plant installed by a Power Supply Authority to give the same service, because a Power Supply Authority must necessarily incur a heavy capital cost in providing the necessary cables and overhead lines to transmit the power which they produce, and must incur maintenance charges on this transmission system.

The average capital cost per kilowatt installed by the five municipal undertakings already referred to is given by the official returns, and the average works out at £48 per kilowatt installed, a much greater cost than that at which a steelworks can install its own plant. This gives a steelworks an additional advantage in reducing the cost of power by still further reducing the capital charges per unit of power produced, and the benefit of this advantage is felt both where power is produced from fuel purchased for the purpose as well as where it is produced from a natural heat resource.

If a balance-sheet be prepared, setting down on one side the cost of purchasing power from the local Power Supply Authority and on the other side the cost of power purchased by the steelworks themselves from plant installed for that purpose, and assuming that all costs, such as capital and obsolescence charges, are included, it will be found that if the steelworks' demand for power is large the cost of power produced by the steelworks themselves will be less than that at which it can be purchased from a Power Supply Authority. If, on the other hand, the demand for power is small, the Power Supply Authority can supply power at a cheaper cost than the steelworks can produce it themselves. It will be found that there is a certain demand for power intermediate between the above-mentioned values, at which the cost of production by the works themselves will equal the cost at which it can be bought from the Power Supply Authority, and that the amount of power demand at which these two costs balance will be different in different works, depending on various local conditions, such as the charges made by the Power Supply Authority, the cost of fuel, &c.

IV. POWER PURCHASED FROM AN OUTSIDE SOURCE.

A Power Supply Authority is one of the commercial assets of a district, and this must receive due consideration, but must also be considered on sound business lines. A Power Supply Authority has, as a rule, an advantage over a power plant erected by an iron or steel works, in being able to install generating plant in larger-sized units than are economically sound in a works plant, and consequently can gain an advantage from reduced fuel consumption

and from a reduced capital cost on the generating plant itself when expressed as capital cost per kilowatt installed. This advantage applies, however, only to steam-turbine plant. If gas-engines be used to generate power an iron or steel works can, as a rule, install the largest sizes of gas-engines which are available.

In a case where a works is producing its own power and is considering the question of purchasing power from a Power Supply Authority, they should first ascertain what their own production cost would be if capital were expended to bring the plant up to date, and obtain the opinion of an independent expert on the matter. Having reached this stage they are in a favourable position to negotiate with a power company, but before this stage is reached negotiations are premature, as the works would be at a disadvantage. In cases where it appears desirable to purchase a supply from a Power Supply Authority, due consideration should be given to the consumer's right to develop his own waste power resources at any time and to his being able to determine his agreement with the Power Supply Authority from time to time on the payment of an ascertainable sum. There have been cases where a works, whose power requirements exceeded the limit at which power can be purchased economically from a Supply Authority, still decide to purchase from a Supply Authority in order to avoid the capital expenditure necessary to provide their own plant. Similar precautions are necessary in such cases.

For many rolling-mill purposes direct current power possesses economical advantages over 3-phase power, as pointed out in some detail by the author in a paper read before this Institute in May 1920. Engineers in making a comparison between the cost of purchasing power from a Power Supply Authority, and the cost of producing power by the works themselves, would see that the power in both instances is of the same type, and that any losses in conversion are borne by the proper party. A Public Supply Authority is entirely outside the control of an iron or steel works, whether it be a private company, a public company, or a municipal undertaking. In the latter case it is peculiarly susceptible to political influence; in the former two cases it is also affected in the same way, but to a less degree, as it is safe to say that all Power Supply Authorities operate under Government concessions in the shape of prescribed areas of supply, &c.

UTILISATION OF POWER FOR DRIVING ROLLING-MILLS.

In considering whether it will prove economical to drive rolling-mills electrically or not, careful consideration must be given to the effect of the demand for power required by the different methods of driving. The mill drive is part of the works power equipment, and therefore whatever method of drive is selected cannot be treated separately from the power-station plant or power company's tariff, as the case may be, both of which are affected in greater or less degree by each of the alternative systems of driving that would come under consideration. It will be readily recognised that if they are dissociated the result will almost certainly be increased capital expenditure.

It is known that electrically driven rolling-mills rolling the same type of section under generally similar conditions of output, temperature and size of billet show great variations in the quantity of power consumed, expressed in kilowatt-hours per ton rolled, and consequently there exist marked differences in the working costs of such mills where one might expect that the working costs would be approximately the same. The author considers that the existence of such differences has been too readily accepted by engineers, and that insufficient attempts have been made to ascertain the cause, with a view to the reduction of the working costs to the lowest obtainable. Examples of these differences are shown by the following figures :

Rolling I Beams Weighing 18 lbs. per Foot Run.

Mill A.	.	.	.	.	.	38.7 kw.-hours per ton.
Mill B.	.	.	.	.	.	58.0 " " "
Mill C.	.	.	.	.	.	53.5 " " "

Rolling I Beams Weighing 12 lbs. per Foot Run.

Mill A.	.	.	.	.	.	47.2 kw.-hours per ton.
Mill B.	.	.	.	.	.	63.5 " " "
Mill C.	.	.	.	.	.	72.9 " " "

These figures are quoted solely for comparative purposes, and are not intended as examples of ideal power consumptions.

Cases of high-power costs may be attributable to :

- Improper drafting of rolls ;
- Improper selection of drive ;
- Improper selection of motor ;
- Billets not properly heated ;
- Improper selection of system of power supply to suit local conditions ;
- Gradual introduction of mixed power plants, due to not adhering to the original programme ; and
- Lack of proper records.

The electrical drive gives ample facilities for detecting and remedying cases of high-power costs arising from high-power consumption due to roll drafting, which is unsuitable from the point of view of power costs ; but little has been done in this direction, and no information is generally available regarding the principles to be observed in drafting to obtain cheap costs.

In regard to the question of selection of drive and motor, one finds that to obtain the cheapest power consumption the principle to be acted on is that of keeping all losses, either electrical or mechanical, to an absolute minimum. The attainment of this, however, embraces a great deal of detail engineering work. It is usually found, however, that the arrangement of the plant to attain minimum losses entails increased capital costs, and therefore to obtain the best all-round result, *i.e.* the lowest combined capital and power costs, complete balance-sheets must be prepared to represent the different conditions under which the mill has to work, after consideration of the proposed rolling programme and the manner in which this rolling programme may develop in the future. It then becomes a matter of judgment to select the type of plant to give the best all-round economy under these varying conditions. Generally speaking, greater differences in power consumptions are to be found in mills where the product rolled is of such a character as to require a greatly fluctuated power, than in those where the power taken remains more constant, and consequently the former types of mills are those in which the possible economy is frequently not attained.

Where a mill is rolling less than the full output the power con-

sumption in kilowatts per ton is greater than if it were rolling its full output, as is illustrated by the following figures :

Rolling x Beams Weighing 21 lbs. per Foot from Billets $7\frac{1}{4} \times 7\frac{1}{4}$.

Output. Tons per Hour.	Power Consumption. Kw.-Hours per Ton.
7.2	91.5
13.2	65.0
16.0	62.0
22.7	55.0
35.5	48.0

These figures are quoted solely for comparative purposes, and are not intended as examples of ideal power consumptions.

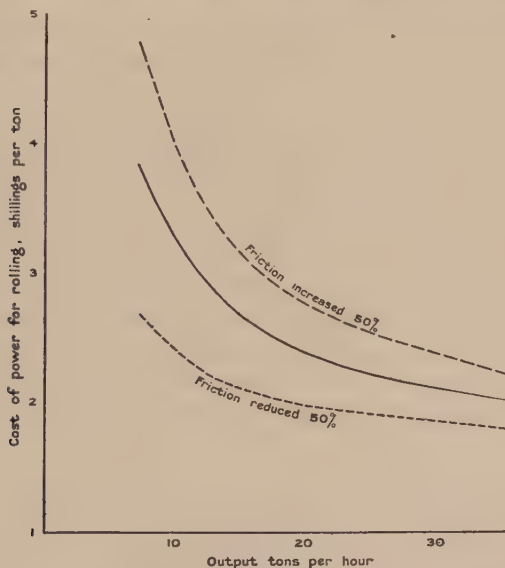


Fig.1 Showing effect of frictional losses on power cost of rolling at different outputs, with power costing one halfpenny per K.W. hour

If it be assumed that the frictional losses of the mill be reduced by 50 per cent., the power consumption in kilowatt-hours per ton stated above would be reduced to the following :

Output. Tons per Hour.	Power Consumption. Kw.-Hours per Ton.
7.2	64.5
13.2	51.5
16.0	49.5
22.7	46.4
35.5	42.8

If, on the other hand, it be assumed that the frictional losses of the mill are increased by 50 per cent., the power consumption in kilowatt-hours per ton stated above will be increased to the following :

Output. Tons per Hour.	Power Consumption. Kw.-Hours per Ton.
7.2	115.5
13.2	80
16.0	73
22.7	63
35.5	53

Fig. 1 shows the effect of frictional losses on the costs of power for rolling at different outputs.

The above tables show that if the power consumption of a mill is high at full output the percentage increase as the output decreases may easily become very great, so that such a mill may become very wasteful indeed when rolling small outputs. This at once suggests an economic problem worthy of the most careful consideration, as we come to a case where to secure the best power consumption the increased capital charges have to be distributed over a small tonnage, while, on the other hand, if the capital charges are kept too low heavy power costs per ton will be incurred.

In conclusion, the author advocates that the engineering side of an iron or steel works should be treated in the same manner as the commercial side, in that it should be the subject of a series of regularly prepared balance-sheets, which should be subjected to scrutiny at stated intervals.

The author wishes to express his best thanks to his partner, Mr. Edward Barrs, for the assistance which he has afforded him in the preparation of the paper, and for the numerous power-plant results which he has placed at his disposal.

DISCUSSION.

Mr. WALTER DIXON (Glasgow) thanked Mr. Ablett for bringing the economic aspect of the subject before the Institute. The paper presented a phase of the subject which would appeal to and meet with the general approbation of all those who considered the matter. Obviously, if the output of a mill running at full load could be taken at three times that of the same mill running at one-third load, the economics of the charges were entirely different, as shown by the paper. To get three times more work out of anything, whether a generator or a mangle, was obviously cheaper.

The author had made some very trite and sensible remarks with regard to the use of exhaust steam turbines and mixed pressure turbines, which, while they had done good work in their day, were likely to give, in many works where they continued to be employed, economically disastrous results. The trouble was that they were so often not bad enough to discard and not good enough to retain.

The author had also made some wise remarks on the subject of gas-engines. It had always to be borne in mind, however, that the prime object of a steelworks was to produce steel—or, at any rate, that had been the case hitherto. The economic question was an important one, of course, but, while the author was correct in what he said with regard to it, there were many factors which had not been taken into consideration in the paper, but which might alter somewhat the conclusions therein arrived at. Was it not Captain Cuttle who said, "The bearings of these remarks depends upon the application of 'em"? That was the case with the paper under discussion. It was full of what might be called self-evident wisdom, but the application of that wisdom depended upon a dozen and one points which were not mentioned in the paper. He would quote, for example, the instance of a Power Company with a load factor of 0.2, whereas the steelworks had a power, or rather a load factor, of 0.6 or 0.7. It might be held that, in such a case, the power could be made more cheaply than it could be supplied, and in principle that was right; but there were many cases where it would not turn out to be so in practice. In theory he agreed with the author's deductions, but it depended on circumstances how far it would be wise to apply them in practice.

Mr. FRED CLEMENTS (Rotherham) thanked the author for bringing the subject forward so clearly and concisely. Under "(a) High Load Factor," Mr. Ablett gave two tables for the cost of power—first of all generated with steam plant, which he supposed referred to gas-fired boilers and high-pressure steam-turbines, and secondly with slow speed gas-engines. At the present time, a steelworks of fairly large capacity

would not demand much more than 6000 kilowatts in the generating station. The question to some extent depended on the class of unit the author was allowing for when arriving at the costs he showed, and he would like to know what size of units the author had in view, and also whether the capital depreciation of spare units (if spare units were to be allowed for) was provided for.

In the case of the water, oil, and stores for steam plant, the figure at 65 per cent. load was 0·02d., while for gas-engine plant it was 0·03d. with the same load factor. He would like to know whether the author included in those figures for the steam plant the cost of preparing boiler water and dealing with condenser water. It seemed to him, moreover, that the figure of 0·03d. was a low one for the gas-engine plant. It depended largely, of course, on the size of the unit employed.

He had lately investigated, with considerable interest, the recent developments in gas-engine practice in Belgium, and had found that gas-engine units were running successfully there at the present time which would develop 6000 kilowatts. Those, he imagined, would be about the largest gas-engines in the world, and, as examples of the highest class of mechanical engineering, they were, in his opinion, unsurpassed; he had never seen anything else to approach them. That development was largely due to the fact that the builders, Messrs. Cockerills, had adopted the policy of increasing the average temperature throughout the gas explosion cylinder, and the engines were running regularly at 80 to 85 lbs. mean effective pressure, instead of 60 to 65 lbs., which had previously been looked upon as the maximum, with consequent increase in the power developed by a unit of given size. It seemed to him that, with the adoption of larger units, the cost of generation on the gas-engine side would be materially reduced. He would like to have the author's opinion on that, because it was well known that he was in touch with all the various points involved.

Mr. L. ROTHERA (St. Albans) thought that all the points raised by the paper were of great importance. Perhaps the chief point on which stress could be laid occurred towards the end of the paper, where the author dealt with the utilisation of power in the driving of the rolling-mills. The chief causes of increased power costs were pointed out, and the importance of those had, he thought, up to the present been somewhat overlooked. An intending purchaser frequently laid great stress on the efficiency of the electrical plant, and a difference of 1 per cent. was considered a matter of great importance. In actual practice such a difference in efficiency was absolutely negligible compared with the loss that took place in the mill itself. Fig. 1 in the paper showed the effect of an increase or decrease of 50 per cent. in the friction loss of a mill. He knew of actual cases where a difference of as much as 30 per cent. had occurred, due to out-of-alignment of the mill, and such an increase would have proved almost impossible to detect with

a steam-engine drive. One of the advantages of the electric drive was that such an increase was immediately detected on the recording instruments and the friction loss could again be reduced to normal.

The only other point he desired to mention was the question of load factor. The author assumed a high load factor as the natural resource of a steelworks. It should be pointed out that the load factor was not necessarily high unless proper steps were taken to that end, but the potentiality was there. The author had not made it clear in the paper what steps should be taken to take advantage of that potentiality, and he could perhaps state what he had in mind as the correct means to that end, apart from an increase in the amount of plant supplied from the power station.

Mr. FRANK ANSLOW (Glasgow) thought most of those responsible for the installation of electric and other generating plant were fully aware of the importance of load factor. On the other hand, those who were responsible for the management of steelworks (he meant the economic management) were not quite so well aware of it as they might be. It was therefore all to the good that the author should have referred to the point, which became particularly evident in the case of the utilisation of exhaust steam and other possible sources of waste heat.

The author quite rightly remarked that, before the installation of exhaust or mixed pressure turbine plant, the problem should be very closely considered. There could be no doubt that the load factor had a very great bearing on that, because the capital expenditure involved was large, and, while the author put the load factor in a steelworks in the neighbourhood of 65 per cent., there was one important consideration which had to be borne in mind in regard to many of those problems, namely, that many iron and steelworks at the present time were connected with collieries. The colliery load factor was not nearly so good as the steelworks load factor. In view of the fact that collieries usually worked one single eight-hour shift only, and at best two shifts, the load factor was not more than about 35 or 40 per cent. ; 45 per cent. was an exceedingly good load factor for a colliery. If a steelworks were generating the whole supply, therefore, its load factor would necessarily be below the figure for the steelworks only. He drew attention to that because it was a very important matter, and one which must be taken into consideration.

He would like to emphasise the author's point that a saving of 15 per cent. or so in the coal bill did not necessarily mean a 15 per cent. saving in the total cost. Considerable developments were being made at the present time in the utilisation of powdered fuel. He agreed that, under the right conditions, powdered fuel was going to be a great asset to many iron and steelworks ; but, having in view the importance of load factor and other similar considerations, he thought there was, perhaps, a tendency to overdo the utilisation of that and

similar developments without first giving the matter the close consideration which it should receive, not only as applying to any individual part of the plant, but its effect upon the economic running of the works as a whole.

CORRESPONDENCE.

Mr. G. M. BROWN (Sheffield) wrote that in his opening sentence the author had stated clearly the guiding principle to be observed in the design of a manufacturing plant, but his treatment of that principle in detail was open to discussion.

The natural source of power available in iron and steel works was heat, whether in the form of combustible gases occurring as by-products from particular processes, the sensible heat of waste gases, or the heat of exhaust steam. It was not easy to see why the author had placed the latter in a class by itself, except that its use frequently involved the retention of obsolete plant and its perpetuation.

The idea of regarding load factor as a natural resource was novel, to say the least, for the advantage of a good load factor was not confined to cases in which the necessary power was generated in the works; many power suppliers based their tariffs on a standing charge per K.W. or K.V.A. of maximum demand and a separate small charge per unit consumed.

In any case the figures quoted by the author were too high. There were only 8760 hours in a year and the average load during working hours was always considerably less than the maximum demand, even though the latter were measured over twenty minutes or half an hour. Thus to attain to a load factor of 65 per cent. it would be necessary to work at the full rate of production for much more than 5700 hours of the 8760 available. The average working year was more like 5000 hours, and if the average load during working hours were taken as high as three-fourths of the maximum demand the load factor did not work out to more than 43 per cent. As a matter of fact it was generally less than that, even in the very largest establishments, and the increasing introduction of mills of the continuous type did not tend to improve it.

As far as concerned the load factor of five of the largest municipal plants in Britain, it seemed desirable to point out that the figure of 21·48 per cent. quoted by the author applied to a period of great and unexampled trade depression and that under normal conditions the figure would have been some 50 per cent. higher.

The tabulated figures given on pp. 227 and 234 of the paper were by implication a comparison of the costs that might be expected from a large steelworks and a municipal or supply company's plant, and in view of the facts stated above, were altogether misleading. In the case of the private plant apparently no charge was to be made for the

gas or the cost of collecting it, and the author's figures did not seem to include any adequate allowance for the cost of cleaning it.

The statements as to the advisability of using blast-furnace or coke-oven gas for heating furnaces rather than as a source of power required some qualification, for in many cases there was no coke-oven gas available to supplement and enrich the blast-furnace gas, and the latter could then be used only for reheating furnaces and soaking pits, so that it would be necessary to use additional coal for open-hearth furnaces, and there would be plenty of gas for power purposes.

In connection with the use of direct current in preference to alternating current, it would be found that the cost of conversion had ultimately to be borne by the consumer. In view of the statement that the conditions of output, &c., were similar, he (Mr. Brown) found some difficulty in accepting the figures of power consumption given on p. 237 of the paper. The differences were too great to admit of any reasonable explanation other than that the mills B and C were not working at anything like full capacity.

With two similar mills improper drafting of the rolls was only indicated by excessive variation in the power requirements from pass to pass, and generally speaking, if the same section were rolled in the same number of passes the power consumption per ton rolled would show no appreciable variations.

Improper or unsuitable design of the electrical equipment would cause far greater discrepancies than mere variations in roll drafting. Any unnecessary increase of the number of passes increased the power consumption at once. The object of all commercial engineering was not, as the author pointed out, to keep down all electrical and mechanical losses, but to reduce the total cost of production to a minimum, and of that cost the power bill was usually a comparatively small item compared with wages and cost of materials. Steel billets might be produced with an average total consumption of power, from the steel furnace stockyard to the truck, of 70 units per ton. It was conceivable that by careful engineering a saving of a shilling or two might be effected on the cost of that power, a difference which could quickly be lost many times over by carelessness or waste elsewhere.

The power consumption per ton was affected by the rate of output, but that was a variation which might be notably reduced by careful management and the avoidance of all unnecessary idle running. If due attention were paid to that point the variations might be considerably smaller than those figured by the author. He had apparently visualised a mill with a friction loss of some 370 kilowatts engaged on a product requiring a net input of 38·1 kilowatt-hours per ton, and assumed that the condition of the mill might vary in such a manner that the friction loss ranged from 185 to 555 kilowatts. He had apparently assumed that the mill was kept running continuously, whether the output was 7·2 tons or 35·5 tons per hour. Sheet and

tinplate mills had to be kept running as long as the rolls were hot, but in other cases it was general to shut down between heats, and in such cases Mr. Ablett's figures ceased to have any meaning.

Mr. ABLETT wrote in reply as follows: "It has been very kindly said in the discussion that the author's paper is full of what might be called self-evident wisdom. It follows, therefore, that the essential principles which have been laid down in the paper, and have been referred to thus, are those to be applied in practice in order to obtain the best return on the capital expended.

"It has also been remarked that the prime object of a steelworks is to produce steel. The author, however, would prefer to qualify this by saying that the prime object is to produce steel economically, and the paper has been written with this end in view.

"In preparing the tables on pp. 227 and 234, it was assumed that 6000 kilowatts of plant would be actually running, but that in addition to the plant actually running there would be 50 per cent. of spare plant, so that there would be 9000 kilowatts of plant installed. The capital charges given in the tables are calculated on the whole of this 9000 kilowatts of plant, *i.e.*, both on the running plant and the spare plant. The figures in the tables include the cost of dealing with condenser water, but in preparing the tables it was assumed that the feed-water for the boilers did not require treatment.

"The remarks which have been made about the Belgian gas-engines are of very great interest, because it would appear that if the Belgians had succeeded in materially increasing the average temperature in the cylinders of the gas-engines, they were on the path to a considerable advance.

"Such an increase in temperature would lead to the introduction of larger gas-engine driven units, and to a cheapening in the cost of gas-engine plant per kilowatt installed. This would probably lead to a reduction in the cost of producing power by means of gas-engines.

"The author is fully in agreement with the remarks made by Mr. Rothera about the potentiality of high load factor in steelworks. It is, however, difficult to make any general statement about the means to be taken to take advantage of this potentiality, because conditions vary so greatly in different works. A general statement therefore has much less value than an investigation of the steps to be taken to increase the load factor of a particular works which would deal fully with the conditions in that works.

"It is very opportune that the question of powdered fuel has been raised in the discussion as the chain of reasoning applied to high pressure steam turbine plants on pp. 230 and 231 of the paper is also applicable to powdered fuel and to other methods of obtaining fuel economy.

"The author is much interested in Mr. G. M. Brown's contribution, but considers that Mr. Brown has not applied the economical principles outlined in the paper. If he had done so he would have arrived at

different conclusions from those given in his letter. He assumes that under normal conditions of trade the load factor of the five largest municipal plants in Great Britain would have been 50 per cent. higher than the figure of 21·48 given in the paper.

"The fact, however, is that during the height of the trade boom the actual figure for these same plants was 24·86 per cent., or 15 per cent. higher than the figure given in the paper, not 50 per cent. as Mr. Brown assumes. The difference between 21·48 per cent. load factor and 24·86 per cent. load factor makes no material difference to the value of the high load factor as a natural resource of an iron and steel works. Mr. Brown has also made some assumptions in regard to the rolling-mill section of the paper, and as these assumptions are not correct, they have not led to correct conclusions. He has also referred to the effect of continuous mills on load factor, and it is of considerable value that this question should be raised, because unless careful attention is given to the whole question of power supply and drive of continuous mills, it can easily be found that such mills are costly in power.

"The author is quite in agreement with Mr. Brown's statement that the object of commercial engineering is to reduce the total cost of production, but Mr. Brown goes on to imply that it is not worth while to effect reductions in the cost of power, as such reductions can easily be lost many times over by carelessness and waste elsewhere. Why, the author would ask, should not the carelessness and waste be reduced as well as the cost of power?"

Iron and Steel Institute.

SOME PROPERTIES OF STEELS CONTAINING GLOBULAR CEMENTITE.

By CECIL H. DESCH, D.Sc., Ph.D., F.R.S., AND AUBREY T. ROBERTS, M.Sc.

THE work described in the present paper was undertaken in order to determine certain properties of high-carbon steels in which the cementite has been brought completely into the globular condition by combined thermal and mechanical treatment. The first section deals with the effect of heat treatment on a carbon steel (1.28 per cent. carbon) slowly cooled from the molten state, and heated under such conditions as to produce globular cementite. Belaiew ⁽¹⁾ has shown that it is under such conditions that a damascened structure is obtained. In the experiments now described, the forging was not carried so far as to yield damascened steel, but some observations supplementary to those of Portevin and Bernard ⁽²⁾ were made regarding the process of agglomeration of the cementite. Mechanical tests of the same steel in three different states have also been made, together with hardness and impact tests of steels of lower carbon content for purposes of comparison. The second part of the paper describes experiments on the steels used in the manufacture of safety-razor blades, with an account of the factors which determine their efficiency. It was remarked by Stead ⁽³⁾ that the cementite in these blades is in the globular condition.

PART I.

The high-carbon steel required for the experiments was prepared in the Metallurgical Department of the University of Sheffield.

A charge of best Swedish converted bar and white pig iron, weighing about 112 lbs., was made up and melted by the usual Sheffield crucible process in two crucibles. When molten, about 16 lbs. from each was cast, aluminium and ferro-manganese

necessary for the remaining 80 lbs. was added to one crucible, and the contents of the other poured in, the cover was replaced, and the charge left to cool very slowly in the furnace, roughly ten hours elapsing before 600° C. was reached. When cold, the ingot was removed and all the rough surface was turned off. The resulting block was a cylinder of 4 inches diameter and about 10 inches long. This was sawn up into discs of 2 inches thickness, which were then ready for forging. This is steel "A" in Table I.

TABLE I.

Analyses of Steels.	Carbon.	Manganese.	Silicon.	Sulphur.	Phosphorus.
A	1.28	0.8	0.061	0.06	0.04
B	0.2	0.45	0.030	0.05	0.04
C	0.45	0.55	0.025	0.04	0.05
D	0.71	0.61	0.041	0.03	0.04
E	0.90	0.52	0.030	0.05	0.04

Small specimens were cut from the cast mass and subjected to heat treatment. The steel was found to have a very coarse structure, the cementite cell walls and crystals being shown in Micrograph No. 1, Plate IX. The structure of the grain boundaries is shown, more highly magnified, in Nos. 2 and 3, the branched cementite being, as Beliaiew has shown,⁽⁴⁾ characteristic of high-carbon steels very slowly cooled from the molten state.

Heating below the Ac1 point produced little change. Prolonged heating caused the pearlitic cementite to become globular without affecting the boundaries. It was therefore decided to conduct heating experiments in the range between the A1 and Acm points. Nos. 4 and 5 (Plate X.) show the effect of heating for one hour at 850°, and Nos. 6 and 7 (Plates X. and XI.) that of heating for four hours at the same temperature. In each case lamellar pearlite has been re-formed during cooling, but extensive changes have occurred in the proeutectoid cementite. The boundaries of the large grains have been disintegrated and new grains on a much smaller scale have been formed, whilst the large "needles" have broken up into segments or disappeared. As might be expected from

the combined influence of solution and surface tension, the sharp projecting spines are the first to become rounded and then to disappear, as shown in Nos. 5 and 7. The share of the original needles in providing portions of the new cell walls is evident in Nos. 4 and 6.

A disc cut from the same block of steel was forged down to a bar 1 inch square, the forging temperature being about 750° , falling to 700° . This process favours the breaking up of the free cementite, and the more nearly the temperature approaches A_1 , the larger is the quantity of free cementite separated from solid solution, and the more efficient is the conversion to the globular form. This, as Belaiew has shown, is the condition for the production of damascened steel. In the experiments now described, however, no damascened macrostructure was observed, probably owing to insufficiently slow cooling of the original fused mass. No. 8 (Plate XI.) shows the structure of steel "A" forged between 750° and 700° , and then annealed for three hours at 670° .

A disc of the same steel was forged at a higher temperature, beginning at 900° and finishing at about 800° . It was found to be more difficult to bring the cementite of this specimen into the globular condition, most of it having been in solution during the forging operation. Prolonged annealing at 670° converted the smaller particles into the globular form, but the larger fragments remaining from the broken boundaries and needles were only slightly affected. Heating at 750° for fifteen hours, followed by six hours' annealing at 670° , brought about the formation of a completely globular structure. In the heat treatment of such forged steels the difference between eutectoid and pro-eutectoid cementite disappears, and any differences in the behaviour of the particles of cementite are to be attributed only to differences of size.

Mechanical tests were made on the steel in three states, namely :

(i.) Normalised.

(ii.) Having the cementite rendered partly globular by forging between 900° and 800° and subsequently annealing for five hours at 750° and three hours at 670° . The structure is shown in No. 9 (Plate XI.).

(iii.) With completely globular cementite, obtained by forging between 750° and 700°, and annealing for four hours at 670°. These times were adopted after making numerous tests with micro-specimens.

The results of the mechanical tests are shown in Table II.

TABLE II.

	Maximum Stress, Tons per Sq. In.	Yield Point, Tons per Sq. In.	Elastic Limit, Tons per Sq. In.	Elongation on 5 inches, Per Cent.	Reduction of Area, Per Cent.	Izod Impact in foot-lbs.	Brinell Hardness No.
Normalised . . .	50.0	23.5	22.0	4.5	4	1.5	286
Partly globular . . .	39.5	19.5	18.0	20.5	25	1.5	189
Completely globular . . .	37.0	17.0	12.5	26.0	30	1.5	179

The elastic limits were determined on the tensile test-pieces by means of a Cambridge extensometer reading to 0.001 millimetre. The mechanical properties change progressively with advancing conversion of cementite to the globular form.

The low Izod value was unexpected. The normalised specimen was naturally brittle, owing to the presence of large grain boundaries of cementite, but the forged and annealed specimens might have been expected to give better results. Quenching experiments showed that the rate of cooling from 670° was without influence. The point was further investigated by means of Izod tests on the crucible steels lettered B to E in Table I. Portions of these steels, taken from the stock of research steels in the department, were normalised and tested in the following states :

(a) As normalised.

(b) After heating at 670° for the minimum time required to render the cementite globular,

whilst the two steels C and D were also examined after heating at 670° for sixty and also for 150 hours. The progress of coalescence was watched by the examination of micro-specimens heated in contact with their respective test-pieces. The time required for the disappearance of all lamellar pearlite in each case is 24 hours for steel B, 23 for steel C, 20 for steel D, and 18

for steel E. The variation of these values with the carbon content is shown in Fig. 1. The impact values fall sharply as the result of the conversion of lamellar into globular cementite,

TABLE III.

	A.		B.		C.		D.		E.	
	Izod.	Brinell.	Izod.	Brinell.	Izod.	Brinell.	Izod.	Brinell.	Izod.	Brinell.
Normalised	1.5	286	24 hrs.		23 hrs.		20 hrs.		18 hrs.	
Completely globular	1.5	179	46	129	25	159	10	207	6	271
After 60 hours' heating	...	...	29	121	20	143	7	170	4	228
After 150 hours' heating	...	...	...	...	21	137	8.5	165	...	...
	...	...	...	...	22	131	9	161	...	...

and the effect of further coalescence is to produce a small but distinct rise in these figures. It follows that coalescence proceeds very rapidly at first, and afterwards at a diminishing rate. The

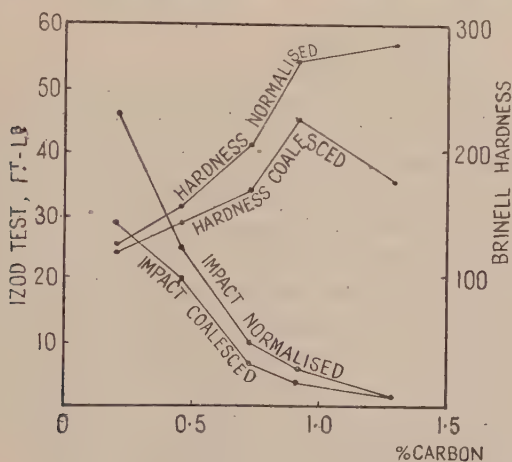


FIG. 1.—Effect of Coalescence.

reason for this is evident when a microscopical examination is made. A typical structure of the pearlite in course of becoming globular after about twenty hours' heating at 670° is shown in Fig. 2, A, the cementite lamellæ having broken up into rows of short rods. After sixty hours, coalescence has proceeded to a

marked extent under the influence of surface tension, a typical structure being shown in Fig. 2, B. The dotted lines in Fig. 2, A, indicate how coalescence occurs. As the surface area of the cementite particles diminishes their distance apart increases, and their difference in solubility becomes less, this being, as suggested by Thompson,⁽⁵⁾ the cause of coalescence. The process, therefore, proceeds with continually decreasing velocity, as is indicated by the change of mechanical properties.

The question of the size of the ferrite grains in such steels is of some interest, and whilst there is no difficulty in revealing the grain boundaries in low-carbon steels containing globular cementite, an examination of published photographs of high-carbon steels in the same condition shows that grain boundaries



FIG. 2.—Coalescence of Cementite.

are rarely visible, and then only incompletely. After trials with several different reagents, it was found that careful etching with Heyn's cupric ammonium chloride reagent could be used for the purpose. No. 10 (Plate XI.) shows the small grains in steel A at a magnification of 1500 diameters. The globules of cementite are frequently, but by no means invariably, at the boundaries of the ferrite grains. After annealing at 670° for a further thirty-three hours, the structure was that shown in No. 11. There was scarcely any increase of grain size, but the irregular boundaries had changed to more nearly regular polygonal forms. This change was accompanied by a small increase in the impact value (from 1.5 to 2.5 foot-lbs.).

PART II.

The subject of the metallurgical character of the thin steel used in safety-razor blades does not appear to have received

much attention. A remark by Dr. Stead to the effect that such steel always contains its cementite in the globular condition has been quoted above. In the present investigation, blades of various makes were obtained in the market, and in addition several samples of blade material, consisting of cold-rolled strips of steel, ready for the stamping operation, were examined. The first series of specimens is shown in Table IV., the structures

TABLE IV.

Type.	Number.	Carbon per Cent.	Chromium per Cent.	Brinell Hardness.
Double-edged .	K (German) .	1.29	0.82	634
" " .	L (American) .	1.39	nil	601
Single-edged .	M (Canadian) .	1.32	0.29	634
Double-edged .	N (English) .	1.09	nil	601
" " .	O (English) .	1.21	...	555
<i>Blade Material :</i>				
Strip . .	P (English) .	1.07	0.05	171
" . .	Q (English) .	0.94	...	178
" . .	R (German) .	1.03	0.62	153

being represented in Nos. 12 to 19 (Plates XI. to XIII.), all being photographed at a uniform magnification of 400 diameters, after etching in a boiling alkaline solution of sodium picrate. All the specimens, hardened and unhardened alike, consist of minute globules of cementite embedded in an apparently structureless ground-mass. The small quantity of chromium present in some of the specimens is without any essential influence on the structure.

Specimens of the three materials P, Q, and R were heated to 850° C. for fifteen minutes, without producing any visible change of structure. Heating to 900° for the same period was also without effect, but after thirty minutes at that temperature, or fifteen minutes at 950°, some lamellar pearlite was found on cooling. After a short time at 1000° a recrystallised structure was obtained, but even after such treatment many particles of globular cementite remained unchanged. The conclusion that solution of such isolated, approximately spherical masses takes place only very slowly is thus confirmed. These globules serve as nuclei for the deposition of cementite during the subsequent cooling, so that lamellar pearlite, which requires an appreciable

amount of undercooling for its formation, is not produced. This fact was demonstrated very clearly by Whiteley.⁽⁶⁾ That some solution does occur is shown by the results of the hardness tests in Table V.

TABLE V.

Quenching Temperature in Degrees C.		710°	740°	770°	800°	830°	860°	890°	920°	950°
Brinell Hardness Numbers	P	156	161	178	180	203	362	514	555	634
	R	178	187	192	197	203	475	605	651	713

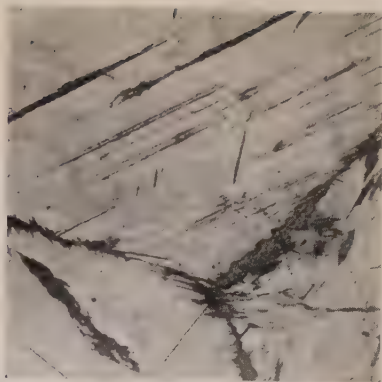
After heating for 25 minutes at 1000° the structure shown in No. 20 (Plate XIII.) was obtained, the steels P and Q being practically indistinguishable. In this condition the Brinell hardness was 220.

In the manufacturing process, the steel strip is brought into the proper condition by rolling and annealing at a low temperature. The structure of the strip at this stage is of the utmost importance to the process of manufacture of the blades, as the arrangement of the particles of cementite is not affected by the subsequent treatment.

Several methods of hardening the blades are used in practice, but in the present experiments only one of these was adopted, blades stamped from the strip being hardened individually between cast-iron blocks, and then tempered between heated steel plates. In the actual experiments small pieces 1 in. \times $\frac{1}{2}$ in. of the strip were rapidly raised to the required temperature in a platinum-wound electric resistance furnace, the junction of the thermocouple being close to the strips, and then each specimen was quickly lifted out and placed between two cast-iron hinged blocks, the lower measuring 6 in. \times 7 in. \times 1 in., and the upper 5 in. \times 5 in. \times $2\frac{1}{2}$ in. The end of the tongs was kept as nearly as possible at the temperature of the strips, by resting in the furnace when not in use for transferring the specimens. The temperature of the furnace was controlled, so that it rose at the rate of 100° in seven minutes, which enabled the experimenter to remove one specimen at a given temperature and to insert another, so that it would be fully heated by the time that the next hardening temperature was reached.



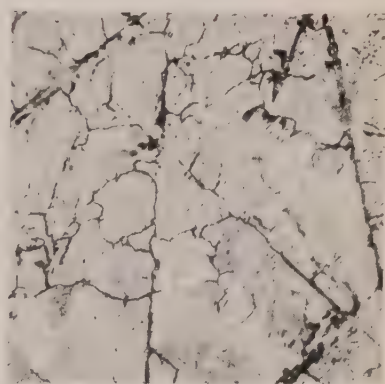
No. 1. Grain structure of the ingot of Steel A. Etched Picric Acid. $\times 20$.



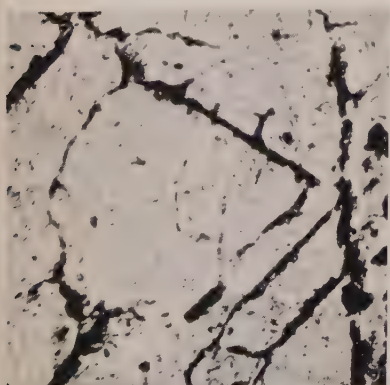
No. 2. Boundary structure in the ingot of Steel A. Etched Sodium Picrate. $\times 200$.



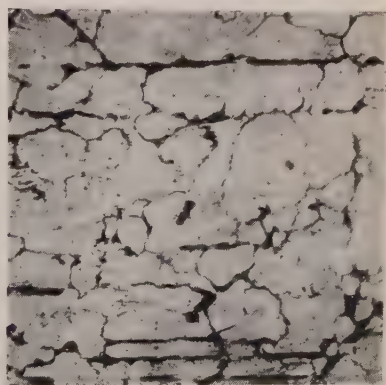
No. 3. Boundary structure in the ingot of Steel A. Etched Picric Acid. $\times 650$.



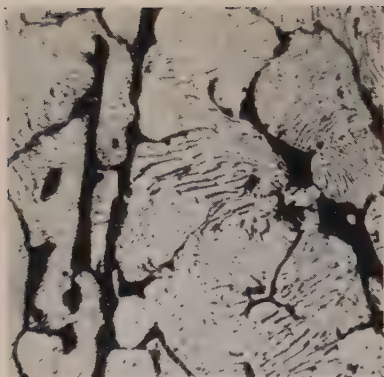
No. 4. Steel A after 1 hour at 850°C . Etched Sodium Picrate. $\times 200$.



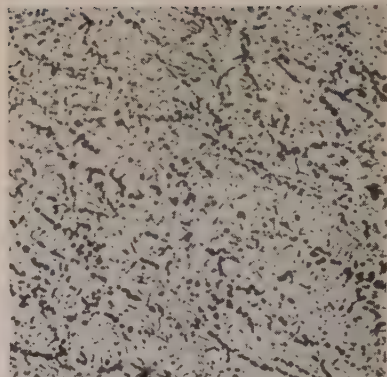
No. 5. Steel A after 1 hour at 850°C . Etched Sodium Picrate. $\times 650$.



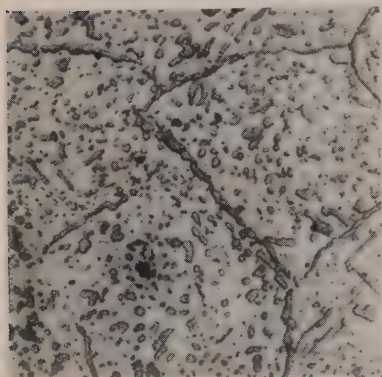
No. 6. Steel A after 4 hours at 850°C . Etched Sodium Picrate. $\times 200$.



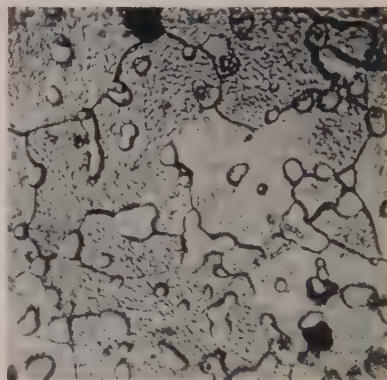
No. 7. Steel A after 4 hours at 850° C.
Etched Sodium Picrate. $\times 650$.



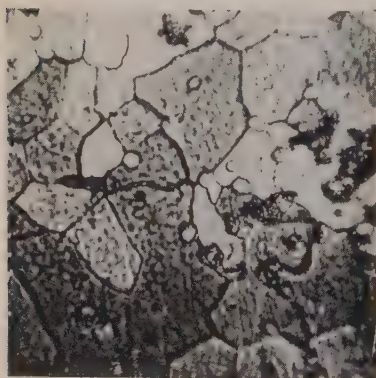
No. 8. Steel A forged between 700° and 750° C. and annealed 8 hours at 670° C.
Etched Sodium Picrate. $\times 200$.



No. 9. Steel A forged between 800° and 900° C. and annealed 15 hours at 750° C. and 6 hours at 670° C. Etched Sodium Picrate. $\times 200$.



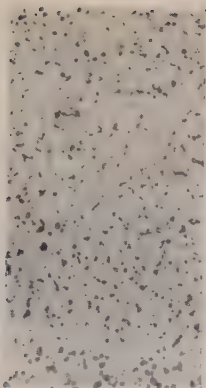
No. 10. Grain structure in "spheroidized" steel. Etched Heyn's Reagent. $\times 1500$.



No. 11. Grain structure in "spheroidized" steel after annealing 33 hours at 670° C. Etched Heyn's Reagent. $\times 1500$.



No. 12. Blade K. Etched Sodium Picrate. $\times 400$.



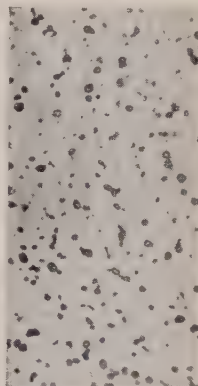
No. 13. Blade L. Etched Sodium
Picrate. $\times 400$.



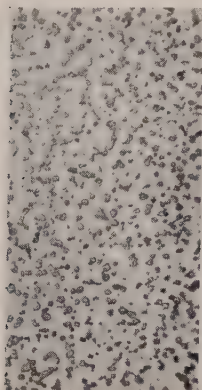
No. 14. Blade M. Etched Sodium
Picrate. $\times 400$.



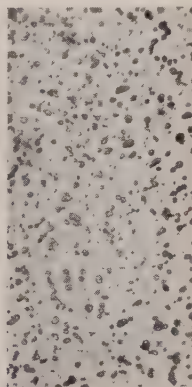
No. 15. Blade N. Etched Sodium
Picrate. $\times 400$.



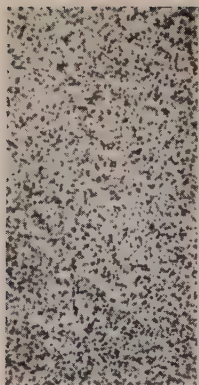
No. 16. Blade O. Etched Sodium
Picrate. $\times 400$.



No. 17. Blade material P. Etched
Sodium Picrate. $\times 400$.



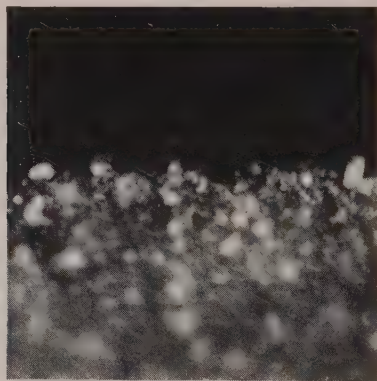
No. 18. Blade material Q. Etched
Sodium Picrate. $\times 400$.



No. 19. Blade material R. Etched Sodium Picrate, $\times 400$.



No. 20. Material P heated at 1000°C . for 25 minutes. Etched Picric Acid, $\times 400$.



No. 21. Edge of blade M. Etched Picric Acid, $\times 1500$.

The hardened specimens were next tightly clamped between a pair of flat steel plates, and heated slowly in a gas muffle until a faint straw colour appeared on the slightly projecting, previously cleaned edges. The clamp and its contents were then quenched in water, and the specimens extracted, buffed on a wheel, and examined for hardness and microstructure. The results in Table V. and Fig. 3 show that the material R attained a greater

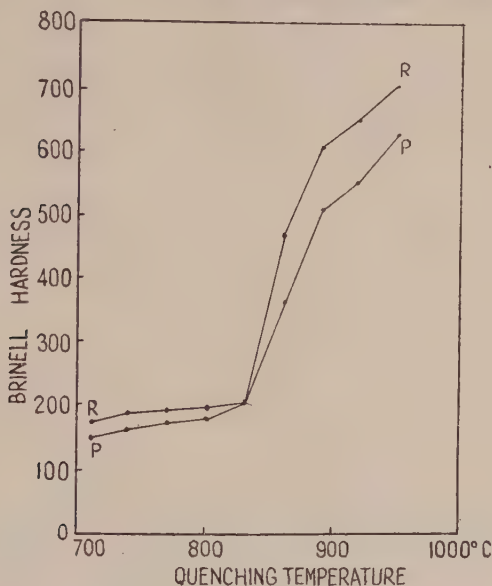


FIG. 3.—Hardening of Blade Materials P and R.

hardness than P, owing to the smaller size of the cementite globules in the former steel. P gave a tempered specimen corresponding closely with blade L in structure and flexibility when quenched at 920°, whilst R quenched at this temperature was too brittle and better results were obtained by quenching at 860°, when the structure resembled that of blade K.

Of the commercial blades examined, L and M were known to have a good reputation for durability. The microscopical examination showed that the distribution of the cementite particles was very uniform, whilst the fineness of the particles was intermediate between the coarsest and finest of the specimens

examined. The martensite forming the ground-mass was without visible structure at the magnification employed.

It may be supposed that the property of "keeping an edge" will depend on the size and uniformity of distribution of the particles of cementite. Examination of blades which have been in use for some time shows that the globules of cementite project beyond the edge. No. 21 (Plate XIII.) shows, at a magnification of 1500 diameters, the structure of a blade of M quality after being in use for a short time. The globules, left white after etching with picric acid, project conspicuously from the edge. It seems probable that the resistance of the blade to wear may depend on the structure, as indicated in Fig. 4. A blade having globules of uniform size regularly distributed, as at A, may wear to the

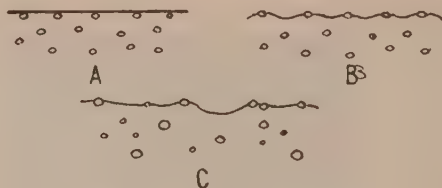


FIG. 4.—Wear of Razor Edges.

form B, whilst a more irregular arrangement would lead to the formation of a jagged edge, as at C. The inferiority of blades N and O, which were known to wear badly, would thus be accounted for. The experiments lead to the conclusion that the quality of the blade is mainly determined by the distribution of the cementite, and that this is little altered by the hardening process. The structure of the strip material thus determines the quality of the finished blade, and it is not possible to correct errors in the manufacture of the original material by varying the hardening process. Further experiments on this point are in progress.

The work on this subject was interrupted, owing to one of the authors leaving Sheffield, and when resumed there was no more material remaining from some of the steels included in the list. Some fresh material was obtained, the properties of which are given in Table VI. The presence of chromium, which is shown by these steels, had not been looked for in the previous

series, but the blade L, which had been taken as a standard, was found to be free from chromium. The values for several

TABLE VI.

Type.	Carbon per Cent.	Chromium per Cent.	Manganese per Cent.	Brinell Hardness.	Critical Points.	
					Ac.	Ar.
Strip S	1·15	0·62	0·39	229	745°	714°
Blade T, single-edged	...	0·44	0·17	668	735°	714°
Blade U, double-edged	...	0·80	0·44	530	736°	706°
Blade V, double-edged	...	0·63	0·26	601	746°	715°

of the steels in Table IV. have since been inserted. The critical points of the later specimens were determined, and the values are inserted in the table.

The authors desire to acknowledge the assistance of Mr. F. K. Knowles, M.Met., in the preparation of the crucible ingots in the Steel Melting Department of the University, and of Mr. J. H. S. Dickenson of the Research Department of Messrs. Vickers, Ltd., in kindly giving facilities for carrying out the forging experiments.

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- (2) A. M. PORTEVIN and V. BÉNARD, *ibid.*, 1921, No. II. p. 145.
- (3) In discussion on Belaiew's paper, *ibid.*, 1918, No. I. p. 438.
- (4) Congrès International de Liège, 1922, p. 548.
- (5) F. C. THOMPSON, *Journal of the Iron and Steel Institute*, 1919, No. I. p. 429.
- (6) J. H. WHITELEY, *ibid.*, 1922, No. I. p. 339.

DISCUSSION.

Professor F. C. THOMPSON (Manchester) said the paper would deserve a hearty welcome if it did no more than give a death-blow to the Japanese heresy that the production of spheroidal pearlite depended on taking the material to a temperature above the A1 point. From time to time Japanese investigators had insisted on that as a necessity, although to English metallographers it had always appeared unnecessary, and was now, by the present paper, shown quite definitely to be so. The authors were to be congratulated on the technique that had been displayed in bringing out the structure of the spheroidal steels at high magnifications. The technique which had produced Photomicro. 10, for example, represented a great advance on anything which, so far as he was aware, had been possible with material of the kind in question up to the present time.

A statement was made on page 254 that, as the temperature was raised, the boundaries of the crystal became more and more straight. That point—that the irregularity of the crystal boundary diminished by heating to higher temperatures—was also shown quite clearly in the paper by Benson and himself (Dr. Thompson) in several steels of lower carbon content. It seemed to be a perfectly general rule that at higher temperatures the crystals became less irregular, and there was therefore less definite interlocking.

The work done in connection with the impact value was of considerable interest. It would have been expected, he thought, that the impact value would rise when normal pearlite was converted into spheroidal pearlite. There was in the latter case a matrix of ferrite, and therefore one might expect something of the order of the impact value of ferrite. The evidence the authors had put forward showing that the impact value was reduced by coalescence was most interesting.

In introducing the paper, Mr. Roberts had said that a temperature about 200° higher than the Acl point was required to cause those large masses of cementite to pass into solution. That statement, by itself, was, he thought, insufficient. So far as he could see, there was no reason to believe that, at the cementite line, the whole of the carbide would not go into solution, provided always that sufficient time was allowed. The time factor operated to a considerable extent in that connection, since diffusion was comparatively slow, but he found some difficulty in believing that, if the time were sufficient, the whole of the cementite would not have gone into solution at the cementite line.

Professor C. A. EDWARDS (Swansea), referring to Fig. 2A of the paper, said he understood the authors suggested that coalescence had taken place, as illustrated in that figure. He was not certain whether that

statement required any qualification or not, but, to his mind, it would seem rather remarkable if two or three isolated globules of cementite were to coalesce, unless something more was postulated than was mentioned in the paper. Surface tension alone would not account for the coalescence of two isolated globules, unless it was stipulated that the intervening phase dissolved one of the constituents; in other words, he would like to ask the authors whether that coalescence was not caused, even if it occurred at lower temperatures than the A1 point, by the solution of one of the globules and the reprecipitation of the dissolved substance on the other. He did not see how surface tension could cause such marked coalescence without some postulate of the kind he had indicated, and he would be glad if the authors would give a more detailed explanation of this interesting side of the subject they had dealt with.

Mr. J. H. WHITELEY (Stockton-on-Tees) said the subject of pearlite in steel was one of perennial interest, and the authors had contributed a very useful paper upon one aspect of it, namely, that of coalescence. He would like, in the first place, to congratulate them upon the excellent photographs with which the paper was illustrated. The fact that spheroidising the cementite caused a lower impact value was mentioned some years ago in a paper by Howe and Levy on coalescence given to Cleveland Institute of Engineers in 1914. Their statement was as follows: "Divorcing annealing in general lessens the impact resistance. In the case of very high carbon steels of 0.92 and 1.45, its effect on the impact resistance is slight." The reason for the low impact values of spheroidised steels might be found in the fact shown in a contribution presented to the present meeting by Messrs. Benson and Thompson that when steels were heated just below the A₁ point for lengthy periods, considerable grain-growth occurred. He noticed in some of the photographs that the carbide particles seemed to be in contact in places. From his own observations he was inclined to think that such particles could remain in contact at temperatures below 700° C. for quite long intervals without coalescence taking place. Actual proof, however, was wanting.

He would like to ask whether any difficulty had been met with in staining cementite by means of sodium picrate solutions? Before using the picrate he (Mr. Whiteley) always etched lightly with a 2.0 per cent. solution of picric acid in alcohol, but could seldom get a uniform stain afterwards; one-half of a particle would stain darkly and the other half remain light with no clear line of demarcation between the two portions. Moreover, in any one grain the relative positions of the light and dark parts on the carbide crystals did not vary and the unstained parts always faced one way.

The effect on coalescence obtained by forging hypereutectoid steels between 800° and 900° C., and subsequently heating them for three hours at 670° C., was very interesting. Could the authors give any

reason why forging and distortion of the solid solution areas at that temperature should subsequently cause the pearlite to break up so quickly? Was there any difference between such a steel forged at that temperature and one allowed to cool down in the ordinary way, so far as the structure of the pearlite was concerned, which would account for that surprising feature?

Colonel N. T. BELAIEW, C.B. (London), said the structure of globular cementite was the structure of damascened blades, which, of course, was one of the reasons why, in addition to the scientific importance of the paper, the results obtained were of such interest. It always took time to bring old processes back to the attention of contemporary scientists and steel makers, and, when it was stated that the structure of the damascened blades was exactly like the structure of some present-day carbon steels, the statement was always (or so it seemed to him) received with a certain amount of incredulity. He felt extremely obliged to the authors, therefore, for having brought before the meeting, in a concise form, the results of their experiments on blades, and for having shown it to be an absolute fact that in many, if not all, the structure was exactly the same as damascene.

On two occasions, the authors stated, they were unable to develop the damascened structure, in spite of the fact that the cementite was entirely spheroidised. The structure of the damascened blades, however, was not the result of the spheroidised structure of the cementite particles; their structure, as was known from the blades in several collections, was the result of the primary structure of the damascened cake. There must be a certain agglomeration of masses of cementite parallel to the axes of the primary crystals in order to show that structure after forging. He suggested, therefore, that one of the possible reasons why the authors were unable to develop the damascened structure was that the primary structure and the axis of the crystals were not sufficiently developed. The old Indian maker was always at pains to produce, first of all, in his damascened cake that primary structure, and only afterwards, with infinite pains, did he try to forge his disc in a certain manner to develop that redistribution of the axes of the primary crystals which would show the wavy structure. The mechanical properties of damascened blades were due, to a certain extent, to that primary structure, and that was the reason why the damascened structure always appealed so much to the Asiatics, and to a certain extent even to Western metallurgists.

The importance of the microstructure, or the importance of getting the cementite spheroidised, lay in the fact that the carbon content in the old damascened blades was so high that it was impossible to forge such high carbon steel when the cementite was in needles in such big agglomerations. It was quite impossible to forge the steel with all those protruding needles, and, in order to be able to forge such a blade, it was first imperative to spheroidise the cementite. That spheroidisa-



FIG. A. Sample of blister steel.
Apo. 2 m/m. (Oil quenched). $\times 1000$.

tion of the cementite was carried out quite fortuitously by the subsequent forgings and heatings which formed a part of the old process. It was impossible to forge a large, or even a small, cake at once, because the heating arrangements were deficient; the temperature would never exceed, say, 800°C ., and, during the forging, it would cool down after a few minutes. The first forging, therefore, would only result in that preliminary breaking up of the cementite lamellæ, which was so brilliantly described in a paper before the Institute in 1918 by Mr. Whiteley. Afterwards, when the cake had cooled down, it was reheated and forged again and again, and all those forgings and heatings (which were applied, of course, quite unconsciously by the old smiths) resulted in the breaking up of the cementite needles and the spheroidisation of the cementite.

In 1906, when examining microscopically some blades belonging to Professor Tschernoff, he (Colonel Belaiew) had been struck by their spheroidised structure, and he remembered that at the time the Professor drew his attention to the fact that in some razor blades there must be that same spheroidised structure. As the authors pointed out, moreover, Dr. Stead, when discussing damascened steel in 1918, also drew attention to the fact that the spheroidised structure existed in razors. In many tools, if the carbon content was high, the maker was, consciously or unconsciously, getting that damascened structure of spheroidised cementite, and the same was true to a certain extent in the case of alloy tool steels. On that account, he had been greatly impressed by photographs Nos. 12 and 19, which showed quite clearly that that was an actual fact. The structure of many blades and many tools, when their carbon content was high, was exactly the same structure as was unconsciously arrived at in India and Persia many thousand years ago.

In regard to the low values obtained in the impact test, he was inclined to agree with Mr. Whiteley that they were the result of the size of the grains. It seemed to him that the grains in the ferrite in the cases in question were larger than the usual and normal grains in ferrite when better impact values were obtained. That was also an important point in the manufacture of damascened blades; it was exceedingly important to get a matrix which was quite uniform, and the matrix of the damascened blades was not like a ferrite matrix. From the point of view of structure it was either martensitic or troostitic.

He was very interested in photos 10 and 11, and had brought with him a photograph made some time ago from a sample of blister steel. He had been trying to get samples with very highly developed pearlite, and had written to Professor Benedicks for some samples. Professor Benedicks sent a sample of blister steel of high carbon content, but instead of a pearlitic there was a perfectly spheroidised structure (see Fig. A, Plate XIII A). That sample was etched for ten or fifteen seconds by 1 per cent. nitric acid, but in spite of that the boundaries between the grains stood out very clearly. He did not

think the boundaries between the grains would be brought out only by special reagents ; he thought it depended very much on the specimens themselves. Under certain conditions it was easy to bring them out by using only nitric acid or a weak solution of picric acid. Under other conditions, however, he agreed with the authors that other and more powerful reagents were necessary. In conclusion, he wished to draw attention to the authors' interesting remarks on the quenching of blades, which seemed to him quite in keeping with the damascene practice, and to congratulate the authors most heartily on their exceedingly valuable research.

Dr. W. H. HATFIELD (Sheffield) said the problem of why a razor would sometimes shave and sometimes not was a very old one in Sheffield, and, much as he would like to do so, he was afraid he could not regard the explanation offered by the authors as being at all convincing. The process of manufacture led to the spheroidisation of the cementite, and when any average razor were examined it would be seen that the spheroids were there. All razors gave the diagram A, B, C, which was simply the little spheroids of hard carbide in a solid solution of intense hardness. The diagram showed a wavy line and an outstanding island of carbide. That would make one think that the matrix of the razor was quite soft and had been eroded, but, as a matter of fact, the matrix of the razor was extremely hard. He would like to know if the authors could give the quantitative relative hardness of the cementite and the solid solution.

The phenomenon which the authors brought forward cancelled out : there could be no doubt about that. No mention was made in the paper of the geometry of the cutting edge, and, after all, it was the craftsmanship of the razor manufacturer which, being given a reasonable hardness, gave either a good or a bad razor. He did not wish to be too critical, but he had given a great deal of attention to the subject, which was a very important one for Sheffield, and the fact was that, after all the inquiries that had been made, it was not possible to say conclusively why razors sometimes were unsatisfactory. However, if they were properly hardened, and the cutting angles anything like what they should be, they would be reasonably satisfactory. Friends wrote to people at Sheffield and said, " Will you send me a really good razor ? " but, try as hard as one liked, and go to the best firms, if it were wished to send a friend a good razor it could not be achieved with any certainty. If the authors were able to show how it could be done, he would be indebted to them ; but, speaking frankly, he did not think their contribution carried the subject any farther.

With regard to Table II., it would have been better if the steels dealt with therein had been more consistent in their manganese content. If the manganese content of steels A and B had been reversed, the low carbon corresponding with the high manganese and *vice versa*, it would have been more useful, in his opinion,

CORRESPONDENCE.

Dr. C. H. DESCH, replying on behalf of both authors, wrote that the photomicrographs, of which favourable mention had been made in the discussion, were entirely the work of Mr. Roberts. With reference to the part of the paper dealing with steel somewhat of the character of Colonel Belaiew's damascene steel, he entirely agreed with Colonel Belaiew that the reason why he and his colleague did not obtain a damascened structure was that the initial structure of the ingot was not of the kind shown in Colonel Belaiew's earlier papers. The cooling was not sufficiently slow. They hoped to repeat the experiment later with precautions to obtain very much slower cooling. Further, the forging necessary to attain a damascened structure was an exceedingly tedious operation. Some experiments had been made in that direction, but the earlier discs, with the most gentle hammering, broke up entirely, and it would take a week or two to forge down a specimen to a reasonable size when the temperature was not allowed to rise above the critical point.

Some reference had been made to the low impact values obtained. They had struck the authors as very curious, but they did not think the explanation was to be found in the large grain size. The grain size in the specimens found was not large. Photographs 10 and 11 were typical of the steels employed, and had low impact values and a grain size which was really very small. A great many experiments were made to determine whether there was something abnormal in the specimens, but up to the present nothing had been found to account for the low impact value; further experiments were, however, to be made.

As Dr. Edwards had said, the explanation given of coalescence involved a certain solubility of the carbides, &c. The authors considered that such a solubility must necessarily be assumed. Dr. Thompson's work on surface tension in steels could not be explained unless that assumption was made. There were, moreover, many other facts for the explanation of which it was necessary to postulate such solubility. It might be small, but unless it existed coalescence could not take place at all.

No difficulty had been found in etching with sodium picrate; it was a method in common use in Sheffield laboratories. Dr. Thompson, when working there, used several alkaline etching reagents and was quite successful.

The reason why the hammering above the critical point should have affected the subsequent spheroidisation was, he thought, that the temperature at which it was being carried out was not sufficient to bring all the cementite into solution; there were cementite cell walls left, and as long as those persisted, a pearlitic structure would be

obtained on cooling down. It was only when those cell walls were completely broken up by forging that successful spheroidisation was obtained.

Turning to the second part of the paper, that dealing with safety-razor blades, the question of ordinary razors had not been touched on, and the observations applied only to safety-razor blades. The structure of the ordinary old-fashioned Sheffield razor was not the same as that of a safety-razor blade; it was much more complex, and the heat treatment was different. With safety-razor blades, made from very thin rolled strip, the facts were very simple. The conclusion at which the authors had arrived was that they could tell a good safety-razor blade from a bad one at once, by etching with sodium picrate and examining under a microscope.

Photographs 13 and 14 showed good safety razors; No. 16, on the other hand, illustrated a typical bad blade. Up to the present the authors had examined a large number of different makes and consignments of blades, and had always found that, in a good blade, the distribution was uniform and the particles were of uniform size. In a bad blade they were irregular. It had been found that that distribution depended on the distribution of the cementite in the original rolled strip. If the rolled strip were in perfect condition good blades could be made from it, but good blades could not be made from a strip which had not been properly and uniformly spheroidised beforehand. After the strip was finished, it was impossible for the razor maker to make such alteration by heat treatment within the limits. In that connection it was of interest to mention that the best blades made in America—those which had the highest reputation as safety-razor blades—were made from strip manufactured and rolled in Sheffield.

The authors were not, unfortunately, able to give Dr. Hatfield any hardness figures; improved instruments had lately been installed in Sheffield University to determine hardness, but when dealing with particles which, at a magnification of 1500, showed a diameter of 1 millimetre, it was difficult to determine their hardness as distinct from that of their surroundings. They agreed with Dr. Hatfield that it would have been better if the steels in Table I. had been more uniform in manganese. They were only used to throw light on a particular point, and were chosen from some in stock in the department.

Iron and Steel Institute.

THE CONSTITUTION OF BASIC SLAGS : ITS RELATION TO FURNACE REACTIONS.

By T. P. COLCLOUGH, M.Sc., B.MET., A.I.C. (PARK GATE
IRON AND STEEL CO., ROTHERHAM).

IN the past, the study of the slags produced in the manufacture of basic steel has mainly proceeded along two lines. One is the investigation of the mineralogical constituents of the cold, solidified material in the endeavour to identify the compounds present—this method is both difficult and unsatisfactory: difficult, because of the nature of the methods of preparation of the samples and the difficulties of identification of the minerals present, and unsatisfactory, because there is little or no direct evidence to show whether the compounds found had any existence in the liquid slag, or have merely been formed by selective crystallisation during freezing. This method, on the other hand, is of considerable utility in the study of the values of different slags as fertilisers.

The alternative method is to take samples of slag under “stable” conditions in the furnace, and to endeavour to allocate chemical compositions to the constituents found. This method, where slag samples alone are taken, appears to be unsound unless the precise condition of the bath, at the time the sample was taken, be known. The nature of the slag present on the surface of the metal is certain to vary from time to time according to the variation in “feeding,” and will also depend upon the nature of the metal with which it is in contact. The two substances—slag and metal—must be considered together.

The principle adopted in the following tests was to study the effect of slags of different composition on the impure metal of the bath and, by studying the relative rates of elimination of the various elements, to form a concept of the reactions which occur and of the nature of the products formed.

All the tests were carried out at the Park Gate Iron and Steel Co., Rotherham, in open-hearth furnaces of 50 to 60 tons capacity,

using mixtures of scrap and hot metal from an "active" mixer. Limestone was added with the charge in all cases, but in some cases no oxide was added until the desired type of slag had been obtained, that is, some time after the charge was melted.

1. MELTING SLAGS.

To determine the nature of melting slags, a number of heats were worked with a limited quantity of limestone in the charge. In every case a perfectly definite constitution of slag was obtained.

During the melting period considerable oxidation of metal is brought about by the action of the furnace gases. The oxide of iron thus formed removes first the whole of the silicon from the metal; the resulting silica forms, with the lime, the basis of the slag. The surplus oxygen from this preferential oxidation attacks the phosphorus in the bath up to a definite limit; beyond this it oxidises the carbon and manganese.

Table I. shows a series of melting samples of slag and metal taken from furnaces working under a variety of conditions, the charges varying from 80 per cent. of hot metal and 20 per cent. of scrap to 50 per cent. of each. Wide variations in the composition both of slag and metal are evident—the silica varying from 10.6 per cent. to 20.4 per cent., and the phosphoric oxide from 11.5 per cent. to 22.2 per cent. It will be noted that these constituents vary in inverse ratio, and the rational analysis of the slags shows a definite relation between the various oxides. The relation found shows that in a melting slag each molecule of phosphoric oxide is associated with four molecules of lime, while each molecule of silica requires two molecules of base, which may be CaO , MgO , MnO , or, to a very small extent, FeO .

This series, therefore, verifies the accepted view that the fundamental slag in a basic open-hearth furnace is essentially composed of molecules of phosphate of lime ($4\text{CaO}, \text{P}_2\text{O}_5$) and molecules of monosilicate ($2\text{RO}, \text{SiO}_2$), RO being either CaO , MgO , MnO , or FeO , together with a little free oxide of iron in solution. In no case has it been found possible to obtain a slag without free oxides of iron, because of the constant oxidising effect of the flame.

TABLE I.

Charge.	Metal.						Slag.						Molecular Analysis of Slags.						
	C.	Si.	S.	P.	Mn.	SiO ₂ .	FeO.	Fe ₂ O ₃ .	MnO.	CaO.	MgO.	P ₂ O ₅ .	CaO for 4CaO.P ₂ O ₅ .	SiO ₂ .	RO required for 2RO. SiO ₂ .	CaO, MgO, and MnO.	Excess of Base.	FeO.	Fe ₂ O ₃ .
K. 3804	1.4	trace	0.033	0.32	0.42	13.8	5.0	2.0	10.52	35.8	7.0	19.25	0.5422	0.23	0.46	0.4201	-0.040	0.070	0.0125
K. 3810	1.69	...	0.021	0.47	0.67	11.6	4.56	1.43	10.52	36.2	7.1	22.24	0.6264	0.193	0.386	0.3476	-0.038	0.063	0.009
K. 3812	1.20	...	0.038	0.42	0.58	13.2	4.1	2.3	10.44	36.4	6.52	21.56	0.6072	0.2033	0.4066	0.3578	-0.0488	0.0507	0.014
D. 9936	0.37	...	0.050	0.268	0.34	15.2	3.5	4.14	9.34	33.4	10.14	18.32	0.516	0.253	0.506	0.468	-0.038	0.048	0.025
G. 7464	0.74	...	0.062	0.46	0.35	20.4	5.53	2.07	11.74	36.8	7.24	11.57	0.3260	0.340	0.680	0.6774	-0.0026	0.0077	0.0013
E. 8012	0.81	0.02	0.028	0.37	0.38	10.6	3.9	3.2	11.34	38.0	5.7	21.34	0.6012	0.1766	0.3533	0.3799	+0.0266	0.0542	0.020
H. 2404	0.87	trace	0.032	0.32	0.39	11.4	3.5	5.3	8.0	37.0	6.8	19.72	0.5545	0.19	0.38	0.3888	+0.0088	0.0049	0.0033

It is clear from the above that the relative amount of phosphorus present in the bath at melting will depend upon the relation between the amount of silicon present in the metal charged and the weight of lime put in with it. If the metal possess a high silicon content while the lime added be small, the bath at melting will have a high phosphorus content, and *vice versa*.

2. WORKING SLAGS.

Tests made show that if the silicate be free from oxide of iron, the fundamental slag indicated above is quite stable, and can be maintained in the presence of the reducing elements carbon and phosphorus. The addition of further oxide of iron to the slag does not appear to have any direct effect on its constitution; the oxide merely passes into solution. The only alteration is that a little more manganese may be oxidised to MnO , with a correspondingly slight increase in the basicity of the slag. This action is very slight, and practically the whole of the oxide added is available for the oxidation of the carbon—which is eliminated rapidly—while the slag approaches more nearly to its simple constitution, as at melting.

If lime be added to a melting slag, a fundamental change takes place in its composition. It appears that manganese silicate is unstable in the presence of free lime. As a result, the lime added tends to replace manganous oxide in the silicate and to form the simple compound $2\text{CaO}, \text{SiO}_2$, and free oxide of manganese.

That a change occurs in the state of the oxide of manganese is shown by the fact that so long as lime is not added the manganese content of the bath either remains constant or falls slightly, whilst on the addition of lime there is an immediate reduction of manganese oxide and an increase of the manganese in the metal—that is, the MnO has been brought into such a state as to be capable of reduction by carbon or phosphorus. This is an exact parallel of the action of lime added to an “acid” slag, when ferrous oxide is displaced from its combination with silica and rendered capable of reduction. Examples of such action will be found in Tables II., V., and VI.

With the addition of more lime than is necessary, with MgO ,

to combine with the whole of the P_2O_5 and SiO_2 present, it is probable that the excess lime forms a fairly stable compound with ferric oxide. To test this two heats were worked with a slag rich in lime but low in oxide of iron. The samples obtained, taken at half-hour intervals, were as shown in Table II.

TABLE II.

	Metal.			Slag.			
	O per Cent.	P per Cent.	Mn per Cent.	FeO per Cent.	Fe_2O_3 per Cent.	CaO per Cent.	MnO per Cent.
F. 5775							
1	1.14	0.346	0.54	3.86	4.43	50.0	6.10
2	1.16	0.308	0.61	nil	4.30	49.2	3.92
3	1.13	0.233	0.61	nil	5.0	50.3	3.92
4	1.10	0.205	0.60	nil	5.0	50.8	3.89
F. 5816							
1	1.38	0.600	0.63	1.93	4.86	41.2	14.9
2	1.36	0.464	0.94	0.56	2.66	48.5	6.4
3	1.39	0.382	0.92	0.36	2.89	49.9	4.8
4	1.37	0.342	0.92	0.35	3.26	52.0	4.4

In view of the fact that Fe_2O_3 is not the stable form of iron oxide at steel-making temperatures, and is very easily reduced, one cannot conceive of its existence in the "free" state in the presence of baths of metal as rich in oxidisable elements as those shown. One is driven, therefore, to the conclusion that the ferric oxide must be present as some fairly stable compound, probably calcium ferrate (as prepared by Stead and others), with a formula $xCaO, Fe_2O_3$.

3. TAPPING SLAGS.

Owing to the danger to the furnace, and the difficulty of keeping the bath under "tapping" conditions, it has not been found advisable to experiment at this stage. It can be stated that in order to prevent any danger of the return of phosphorus to the metal, the slag aimed at should be a mixture of calcium phosphate and monosilicate of lime, with the other constituents in solution.

EFFECT OF SLAG COMPOSITION ON RATE OF ELIMINATION OF METALLOIDS.

Carbon and Phosphorus.—Wilson,¹ in his paper on basic slags, appears to hold the view that the composition of the slag has little or no effect upon the relative rates of oxidation of carbon and phosphorus, for he says : “ The oxidation of silicon, phosphorus, and manganese gives exothermic reactions, and these reactions proceed at the lower temperature and in the earlier periods of the charge. Given the required oxygen . . . the condition of the slag will have no direct influence on these reactions,” while “ carbon oxidation gives rise to a strongly endothermic reaction . . . and this reaction is limited to the higher temperatures in steel-making.” How far this fails to represent the true nature of the reactions which occur may be seen from the ensuing data.

It is common experience that in many heats where low sulphur stock is available, and the use of spar slags avoided, the whole of the carbon is eliminated while the phosphorus is still high. When this occurs the bath is usually “ cold,” the carbon has been oxidised at a low temperature, and quantities of carbon (as cold pig) must be added to cause the circulation of the metal which is necessary to secure the removal of the remaining phosphorus and attain the necessary heat for tapping.

In order to determine the effect of slag composition on the elimination of these elements, tests were made in which the additions of lime and oxide were carefully regulated. Two series of tests were made, and typical heats of each type are given.

Series A.—In this series, no oxide was put in with the charge, and the quantity of limestone added was limited.

In the heat given (Table III.) it was found that the slag formed, when the charge was completely melted, was a mixture of phosphate of lime and monosilicates of the various bases, with a little free iron oxides—both ferrous and ferric. After melting small amounts of oxide were added, but no lime until nearly one hour had elapsed. During this period—the early, low temperature period—the phosphorus and manganese remain

¹ *Journal of the Iron and Steel Institute*, 1920, No. I. p. 281.

TABLE III.

Charge D. 9356.	Metal.				Slag.							Molecular Analysis of Slags.										
	C.	S.	P.	Mn.	SiO ₂ .	FeO.	Fe ₂ O ₃ .	MnO.	CaO.	MgO.	P ₂ O ₅ .	Fe.	P ₂ O ₅ .	CaO for 4CaO,P ₂ O ₅ .	SiO ₂ .	Base for quilted SiO ₂ .	Avail- able CaO.	MgO.	MnO.	Total R.O.	Excess of Base.	FeO.
P.M. 12.2 (1)	0.37	0.050	0.268	0.34	15.2	3.5	4.14	9.34	33.4	10.14	18.32	5.6	0.129	0.516	0.253	0.506	0.084	0.253	0.131	0.468	-0.038	0.048
12.32 (2)	0.27	...	0.261	0.35	15.6	3.2	4.70	9.31	33.2	10.14	17.95	5.8	0.1264	0.505	0.260	0.520	0.088	0.253	0.131	0.472	-0.048	0.045
1.0 (3)	0.19	...	0.218	0.36	12.4	3.98	5.0	7.97	35.0	13.76	15.76	6.6	0.111	0.444	0.2066	0.4132	0.181	0.344	0.112	0.637	0.224	0.055
1.35 (4)	0.10	0.051	0.156	0.31	10.1	5.53	4.7	7.53	36.5	13.76	15.68	7.5	0.1104	0.442	0.1683	0.3366	0.210	0.344	0.106	0.660	0.323	0.077
2.0 (5)	0.09	...	0.101	0.28	10.4	8.10	4.43	7.68	35.5	13.78	14.89	9.4	0.1048	0.419	0.1733	0.3466	0.215	0.344	0.108	0.667	0.320	0.112
2.10 (6)	0.08	...	0.088	0.23	11.4	7.10	5.0	7.48	35.0	13.78	15.68	9.0	0.1104	0.442	0.19	0.38	0.183	0.344	0.105	0.632	0.252	0.10
2.30 (7)	0.06	0.048	0.066	0.22	11.4	7.46	5.70	7.40	35.5	13.90	15.31	9.8	0.1078	0.431	0.19	0.38	0.203	0.347	0.104	0.654	0.274	0.103
2.42 (8)	...	...	...	...	8.4	8.36	7.30	7.19	37.5	13.90	14.06	11.6	...	...	...	...	...	...	...	...	...	...

(NOTE.—Available CaO = total CaO — CaO required for P₂O₅.)

constant, while carbon is eliminated. It will be noted that slags 1 and 2 correspond almost exactly with the composition x molecules of $4\text{CaO}, \text{P}_2\text{O}_5$ with y molecules of monosilicate: the slag is saturated with phosphorus and none can be removed from the metal. At this stage a little limestone was added, and some action on the banks occurred (see rise of MgO). As a result of this slight increase of basicity, sample 3 shows that the oxidation of phosphorus has begun. In samples 4, 5, 6 the basicity of the slag increases rapidly, and the oxidation of

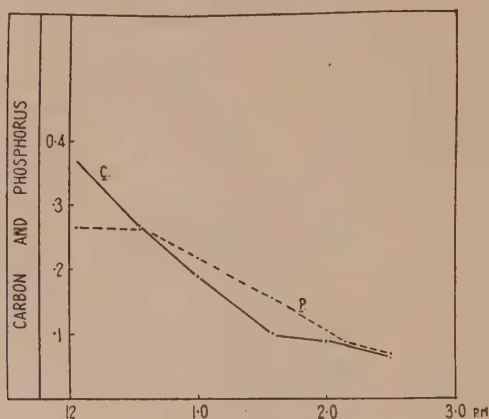


FIG. 1.—D. 9936.

phosphorus proceeds correspondingly, while the carbon remains practically constant (see Fig. 1). This, and its parallel heats, show that the relative rates of oxidation of carbon and phosphorus in the open-hearth process depend primarily upon the state of the slag and not upon the temperature. The amount of phosphorus oxidised depends entirely upon the amount of oxide of phosphorus that the slag can hold, and this in turn is fixed by the excess of base above that required to form a monosilicate with the silica present.

If, therefore, oxide of iron be added to a true melting slag, the basicity is not increased, no more phosphorus can be absorbed, and the whole of the added oxide is free to oxidise the carbon of the metal, even in the early stages, and in the presence of phosphorus.

To put this question of "saturation" composition to a final test advantage was taken of the action of sand, well known to steel-makers, thus throwing phosphorus back from the slag into the metal. Table IV. shows the samples obtained.

The heat was worked as those above to sample 4. It will be noted that the slag, at melting, was saturated with phosphorus, and for the first two hours both carbon and phosphorus were oxidised—the slag becoming almost saturated. From sample 3 there is a return of manganese from the slag to the metal, and simultaneously there is a return of phosphorus likewise from slag to metal. This clearly demonstrates that the manganese oxide must be in combination with the acid constituents of the slag, and that the slag was at its saturation composition. A small quantity of sand was then added to increase the acidity of the slag. Sample 5 shows the effect: more phosphoric oxide is reduced to phosphorus, and the amount reduced is exactly that necessary to bring back the slag to the original "saturation" composition. The phosphorus of the metal was kept constant for samples 7 and 8, after which lime was added and the usual elimination of phosphorus effected.

In every sample, from 1 to 8, the slag had the composition of a true melting slag, $4\text{CaO}, \text{P}_2\text{O}_5, 2\text{RO}, \text{SiO}_2$, and the amount of phosphorus present in the slag was definitely fixed by the amount of available base in the slag. Fig. 2 shows the relative rates of oxidation of the carbon and phosphorus, and from this figure it will be seen how closely the phosphate of the slag follows the amount of available base, the slight discrepancy of sample 5 probably being due to the time factor, equilibrium not having been established. These figures seem definitely to prove that such a slag cannot contain any bisilicate, as suggested by Dichmann in his equations for furnace reactions, and by Wilson in certain of his slags. If the bisilicate of lime (CaO, SiO_2) were stable under these conditions, more base would be available to combine with the P_2O_5 , and more phosphorus would be oxidised. In view of the return of phosphorus to the metal, it seems certain that the bisilicate cannot be present.

The above heats show that there is a minimum "critical" value for the basicity of a slag, below which no further oxidation of phosphorus can occur.

TABLE IV.

Charge H. 2459.	Metal.				Slag.							Molecular Analysis of Slags.							
	C.	S.	P.	Mn.	SiO ₂ .	FeO.	Fe ₂ O ₃ .	MnO.	CaO.	MgO.	P ₂ O ₅ .	CaO for 4CaO,P ₂ O ₅ .	SiO ₂ .	Base re- quired for 2RO ₂ SiO ₂	CaO, MgO, and MnO.	Excess of Base.	FeO.	Fe ₂ O ₃ .	
A.M. 9.10 (1)	1.17	0.038	0.415	0.43	22.10	4.11	3.00	13.85	40.0	2.60	9.2	0.0648	0.2592	0.3663	0.7326	0.7152	-0.0174	0.0571	0.0187
10.20 (2)	0.82	...	0.260	0.34	18.6	5.39	2.7	11.27	37.7	6.90	13.23	0.0931	0.3724	0.310	0.620	0.6320	0.0120	0.0748	0.0169
11.20 (3)	0.45	...	0.222	0.29	17.9	5.78	2.4	11.54	38.6	6.60	13.91	0.0980	0.3920	0.2983	0.5966	0.6348	0.0372	0.0803	0.0150
11.40 (4)	0.38	...	0.259	0.37	18.0	5.10	3.1	10.32	40.1	6.00	12.93	0.0911	0.3644	0.300	0.600	0.6469	0.0469	0.0708	0.0194
P.M. 12.0 (5)	0.27	0.038	0.276	0.39	19.3	4.88	3.6	9.29	40.8	5.3	12.47	0.0878	0.3512	0.3217	0.6434	0.6406	-0.0028	0.0871	0.0225
12.20 (6)	0.22	...	0.288	0.38	18.9	3.85	4.9	9.37	40.8	5.1	11.64	0.0820	0.3280	0.3150	0.6300	0.6600	0.0300	0.0534	0.0306
12.40 (7)	0.18	...	0.286	0.39	19.0	4.75	4.9	9.62	41.0	5.1	11.64	0.0820	0.3280	0.3150	0.6300	0.6671	0.0371	0.0660	0.0306
1.0 (8)	0.10	0.038	0.259	0.36	18.0	4.75	5.0	9.53	41.8	4.9	12.64	0.0873	0.3392	0.300	0.600	0.6639	0.0639	...	...

TABLE V.

Charge M. 2947.	Metal.				Slag.							Molecular Analysis of Slags.									
	C.	S.	P.	Mn.	SiO ₂ .	FeO.	Fe ₂ O ₃ .	MnO.	CaO.	MgO.	P ₂ O ₅ .	CaO for P ₂ O ₅ , 4CaO.P ₂ O ₅ .		SiO ₂ .	Base re- quired for 2H ₂ O. 3CaO.	MgO.	MnO.	Excess of Base.	FeO.	Fe ₂ O ₃ .	
A.M.	0.43	0.035	0.32	0.37	14.6	4.08	4.03	11.9	38.5	5.7	16.0	0.1127	0.4508	0.2433	0.4867	0.2367	0.1425	0.1676	0.0601	0.0567	0.0252
1.0 (1)																					
1.23 (2)	0.36	0.029	0.21	0.43	12.8	4.08	3.45	9.05	42.0	...	16.12	0.1135	0.4540	0.2133	0.4266	0.296	0.1425	0.1275	0.1393	0.0567	0.0215
1.55 (3)	0.31	0.026	0.19	0.55	12.0	4.08	3.45	6.9	44.3	...	16.10	0.1135	0.454	0.200	0.400	0.319	0.1425	0.0972	0.1587	0.0567	0.0215
2.25 (4)	0.31	0.024	0.15	0.49	10.8	4.14	3.83	6.95	46.9	...	15.2	0.1070	0.428	0.180	0.360	0.4095	0.1425	0.098	0.290	0.0575	0.024
2.55 (5)	0.30	0.023	0.05	0.39	9.4	4.88	4.57	7.29	42.5	...	15.0	0.1056	0.4224	0.1567	0.3134	0.3366	0.1425	0.1027	0.2685	0.0678	0.0285
(Slagged)																					
3.30 (6)	0.13	0.020	0.040	0.31	8.6	6.43	5.70	7.54	42.9	...	13.6	0.0958	0.3832	0.1433	0.2867	0.3829	0.1425	0.1062	0.3449	0.0893	0.0356
4.5 (7)	0.13	0.021	0.030	0.25	8.2	9.25	5.60	7.83	44.4	5.1	12.8	0.0901	0.3604	0.1367	0.2733	0.4326	0.1275	0.1103	0.3971	0.1285	0.035

Series B.—If lime be added to a slag of such “critical basicity,” the oxidation of carbon and phosphorus proceeds simultaneously. A good example of this is seen in Table V. In this heat the slag at melting was not quite saturated with phosphorus, a slight excess of base being present. In the first

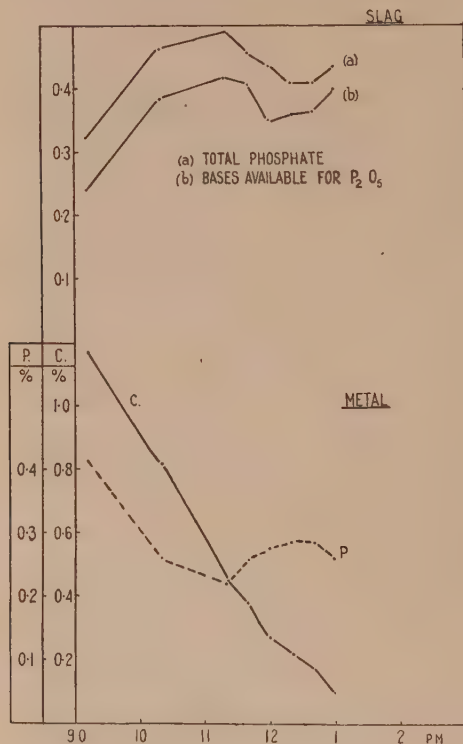


FIG. 2.—H. 2459.

hour, fluorspar (6 cwts.) and limestone (but no oxide) were added. Oxidation of both carbon and phosphorus proceeds at the expense of the oxide of iron produced by the action of the furnace gases and the manganese oxide of the slag.

After sample 3 limestone and scale were added, and at once a change in the rate of reaction occurred. The carbon remained constant at 0.31 per cent. until the phosphorus had been almost completely eliminated, falling to 0.05 per cent. when the slag

was removed (see Fig. 3). It would therefore appear that there is a second "critical composition" of a slag. Whether this, like the former, coincides with the formation of some definite compound is doubtful, but examination of the data suggests that it occurs at the point where the CaO content of the slag is

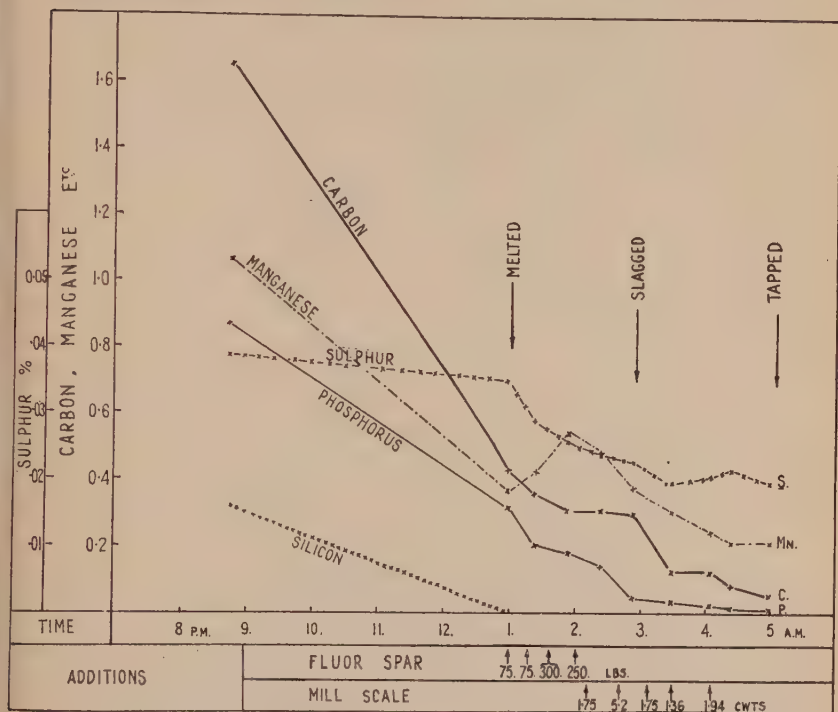


FIG. 3.—M. 2947.

sufficient of itself to form the phosphate and monosilicate of lime. [Note "Available CaO" in Table V.]

To test this, several heats were tried. In each case extra lime was added with the charge, and spar and limestone (but no oxide) were fed immediately after melting. Table VI. shows the nature of the reactions which occur. Throughout the heat the lime in the slag is sufficient to unite with the whole of the SiO_2 and P_2O_5 formed, and still leave an excess of lime ready to combine with any further P_2O_5 as soon as it can be formed,

As a result, thermo-chemical considerations are given full play, and are of first importance in determining the reactions which will occur. Hence there is a great demand for oxygen from the phosphorus—this element having the highest heat of oxidation¹—so much so, that not only is the whole of the FeO of the slag removed but some of the MnO also is reduced, while the carbon remains constant until the phosphorus is reduced to 0.1 per cent. The oxidation of phosphorus then slows down by virtue of its low concentration, and the oxide added becomes available for the elimination of carbon and manganese. Fig. 4 shows the

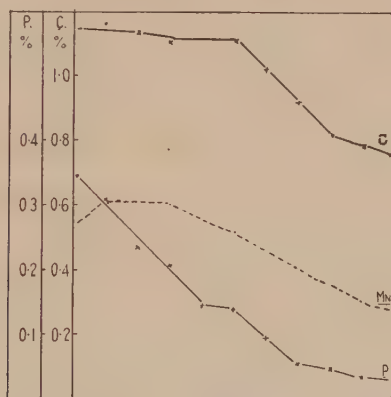


FIG. 4.—F. 5775.

relative rates of oxidation of carbon and phosphorus and is in striking contrast from Fig. 1.

These tests indicate that the composition of the slag plays a fundamental part in determining the reactions which may occur in the furnace. Further, that there are two "critical" compositions :

(a) Where the bases are only sufficient to form the slag $4\text{CaO}, \text{P}_2\text{O}_5$, with $2\text{RO}, \text{SiO}_2$, whereupon no further oxidation of phosphorus can occur, the whole of the available oxygen uniting with the carbon.

	Heats of Oxidation. Calories per Gramme of Element.	Heat of Formation of Slag.
¹ P	5897	2572
Mn	1653	
Fe to FeO	1173	
C to CO	2430	

(b) Where the lime content of the slag is sufficient to provide the whole of the base necessary in (a), whereupon phosphorus alone is oxidised, the carbon not being attacked, but some manganous oxide being reduced.

Within these two limits the oxidation of all three elements proceeds simultaneously, the relative rates being determined by the divergence of the slag from these limits.

DISTRIBUTION OF MANGANESE.

It is well known that the behaviour of manganese in the basic process differs entirely from that in the acid process. In the latter process the manganese is oxidised almost as quickly as the silicon ; the amount left in the metal falls rapidly to about 0.05 per cent. ; the MnO passes into the slag, forming a stable silicate, and, except under abnormal conditions, plays no further part in the reactions.

In the basic process the rate of oxidation is far less rapid, the amount of manganese present in the bath varies within wide limits, and the reduction of MnO from the slag is a common phenomenon (see Tables V. and VI.). The manganese content of the metal at tapping is dependent upon the character of the slag, and heats may be finished with 0.3 per cent. of manganese in spite of the presence of a highly oxidising slag.

The migrations of manganese between metal and slag have been the object of many investigations. Dr. Naske¹ gives a full list of examples showing the reduction of MnO from the slag and the increase of Mn in the bath. He comes to the conclusion that the distribution of manganese between metal and slag depends upon the relative concentrations of MnO and FeO in the slag : if the ratio MnO : FeO exceed unity, reduction of MnO is brought about. Examination of the heats described above shows that no such simple explanation is satisfactory. In every heat given the concentration of MnO in the melting slag exceeds that of FeO, but in only one case was reduction of MnO observed, unless spar and lime had been added and the basicity of the slag increased.

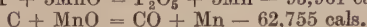
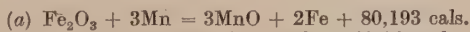
It is certain that the other constituents of the slag have a considerable influence on this reaction. As stated above, the

¹ *Stahl und Eisen*, 1907, p. 158.

condition of the MnO depends upon the basicity of the slag. If the bases be so low that MnO is necessary to form the monosilicate, no reduction is possible, as manganous silicate is not reducible under the prevailing furnace conditions. This is borne out by observations on an "active" mixer, where the slag is always silicious. In this case it is perfectly easy to carry a slag containing 20 to 25 per cent. of MnO to about 5 per cent. FeO, and for oxidation of manganese still to proceed. If the amount of base in the slag be sufficient to form the silicate and phosphate without MnO, the MnO will be present in the free state and be capable of reduction. If Naske's ratio be applied to "free" MnO and FeO, there is still a lack of agreement, for in Tables V. and VI. are shown examples where the MnO content exceeds that of FeO and in which further oxidation of manganese is proceeding.

Dichmann suggests that the reduction of MnO depends upon the total concentration of oxidising elements in the slag. He shows that in all Naske's examples there is a deficiency of FeO, and states, as his opinion, that reduction of MnO occurs whenever the FeO falls below 12 per cent., because the slag is then "poor" in available oxygen. This view is borne out, to some extent only, by the above heats. In them it was noted that the reduction of MnO took place only in the early stages of the "working" period, and under such conditions as gave a low oxide of iron content to the slag. In every case in section B where "free" MnO was present, reduction of MnO proceeded so long as the FeO was low, but no limiting value for FeO (such, for example, as 12 per cent.) could be found, because this action ceased and manganese was at once oxidised and returned to the slag whenever oxide of iron was added.

It would appear that the distribution of manganese depends upon two factors—first, upon whether the MnO in the slag be in the free state or combined with silica; and, secondly, upon a balance between the following reactions:



The elements carbon, phosphorus, and manganese are all in need of oxygen for their elimination. By virtue of its greater heat-giving value, phosphorus oxidation will, other conditions favourable, be preferential, and the formation of MnO will follow.

There will, however, always be the tendency for the inverse reaction of the phosphorus and carbon on this MnO in the slag if it be free.

The *net* distribution of manganese between slag and metal will depend upon the difference in velocity of the reactions (*a*) and (*b*). The velocity of (*a*) will depend upon the concentration of oxide of iron in the slag, as indicated by Dichmann; while that of (*b*) will depend upon such variables as the concentrations of the various elements and oxides present, and also the temperature. So many factors being involved, it would seem impossible to lay down a simple rule stating definitely when this reduction of manganese oxide will occur.

ELIMINATION OF SULPHUR.

There are three processes by which the sulphur content of steel made by the basic process is reduced.

1. The Massenez process, where manganese is added to the liquid pig iron, which is allowed to stand in a mixer furnace. This manganese combines with the sulphur of the metal, and MnS, being soluble in both metal and slag, proceeds, by the well-known Partition Law, to migrate from the iron to the slag. This would continue until the relative concentrations in metal and slag reached a definite value, and then stop, but, owing to the secondary reaction, $2\text{MnS} + 3\text{O}_2 = 2\text{MnO} + 2\text{SO}_2$, the MnS in the slag is oxidised by the furnace gases, and the process continues until practically all the sulphur is eliminated from the metal.

2. The second method is an adaptation of this in the open-hearth furnace itself. Ferro-manganese or manganese ores are added. In the latter case, MnO is reduced to manganese, which passes into the metal. In either case the manganese acts in the same way as in the mixer.

3. Saniter's process. It is now many years since Saniter demonstrated the value of adding fluorspar as a desulphurising agent in the basic steel process, but, hitherto, no rational explanation has been given of the method by which it produces this effect.

Examination of the data collected in this investigation shows a remarkable parallel between the behaviour of the manganese of the charge and the elimination of sulphur.

(a) In all cases where the lime content (and therefore the basicity of the slag) was low, there was a general oxidation of manganese, and no elimination of sulphur. In several cases the sulphur content increased.

(b) On the other hand, whenever spar and lime were added, and the basicity of the slag increased while the iron oxide content was low, there was a reduction of MnO in the slag, with an addition of manganese in the bath, and the removal of sulphur invariably followed.

It is generally agreed that the best way to use spar is to add it immediately after melting, and feed lime but omit oxide. These are precisely the conditions which lead to an increase of the manganese of the metal. Fluorspar and lime are not "direct" desulphurising agents. The addition of spar, giving greater fluidity to the slag, enables it to carry additional lime; this lime displaces MnO from its combination with silica, and finally this free MnO (in the absence of a large FeO content) is reducible to manganese. This manganese, added to the bath, is the "active" agent in the removal of sulphur. It acts in exactly the same way as manganese does in the mixer furnace, manganese sulphide passing into the slag and being converted into MnO and SO₂, which passes away in the chimney gases. If the conditions remain favourable, the MnO is again reduced, and the cycle of operations continues.

Examples of this action are given in Table VII.

TABLE VII.

Cast.		Metal.		Slag.		
		Mn per Cent.	S per Cent.	MnO per Cent.	S per Cent.	CaO per Cent.
F. 5775	Melted	0.54	0.033	6.10	0.040	50.0
	Sample 4	0.60	0.016	3.89	0.043	50.4
F. 5816	Melted	0.63	0.029	...	...	...
	Sample 3	0.92	0.015	...	...	...
D. 9926	Melted	0.62	0.028	6.14	...	...
	Sample 3	0.71	0.017	4.18	...	...
M. 2947	Melted	0.37	0.036	11.9	0.08	38.5
	Sample 3	0.55	0.026	6.9	0.13	44.3
	" 6	0.38	0.020	7.5	0.13	43.0

CONCLUSIONS.

1. The slag formed in a basic open-hearth furnace is essentially tetra-calcic-phosphate of lime with monosilicate of lime, magnesia, and manganese oxide.

2. The addition of "acid" oxides to such a slag causes instability, and leads to a return of phosphorus to the metal.

3. Additions of "basic" oxides merely pass into solution and the type of compound is not altered. In certain cases there is probably a compound of lime and ferric oxide formed, which is comparatively stable.

4. When an excess of lime is present, MnO is carried in solution and, under certain conditions, is reducible to manganese.

5. The relative rates of oxidation of carbon and phosphorus depend primarily on the basicity of the slag, and there are two "critical" compositions :

(a) When the total bases are sufficient only to form the slag given in (1) there is no further oxidation of phosphorus, and carbon is eliminated.

(b) When the lime content is sufficient to form the silicate and phosphate, carbon remains constant until nearly all the phosphorus is eliminated.

6. The removal of sulphur is only indirectly due to the presence of a high lime content—the direct agent is manganese, which is thrown into the bath from the slag.

The author wishes to express his indebtedness to the directors of the Park Gate Iron and Steel Co. for permission to use the data collected in the above tests, and also to his colleagues, particularly Mr. H. Royston, the works manager, for help in carrying them out.

Special thanks are due to the members of the Laboratory Staff, under Mr. C. Armitage, the Chief Assistant, for their careful and accurate analyses of the materials used.

DISCUSSION.

Mr. E. H. SANITER, Member of Council, said the paper was a plain statement of the facts, which should be useful to steel-makers. He thought, however, the author had not given full weight to the rôle played by oxide of iron, and had too greatly insisted on the effect of lime. Oxide of iron played a double rôle in the process; it was, of course, an oxidiser (that was what it was put in for), but in any quantity it was also a very strong base, and could remove the phosphorus independently of the lime. In working a metal where the carbon was to be worked very low it was very often nearly dephosphorised with oxide of iron, and then it was a rush to get enough lime in before the oxide of iron was exhausted; otherwise the phosphorus returned to the metal.

The question of sulphur was one in which he had been very much interested for a number of years. He did not think he could accept the author's explanation in that regard. In the first place, there was a very great difference between the temperature in the Siemens furnace and that at which the reactions took place in the mixer by the Massenez process. In his opinion, sulphide of manganese could not exist at the tapping temperature of the molten steel in the Siemens furnace, for the reason that, when sulphur segregated heavily in steel, the manganese was not always in molecular proportion to the sulphur. He had always held the theory that manganese sulphide was formed at a temperature about the solidifying temperature of steel.

The author, perhaps, attached more importance to manganese because the pigs he was accustomed to work always had a lot of manganese in them. In the Cleveland district, however, where the manganese in pig iron was 0.5 per cent. or less, the desulphurising process was going on, and in the past a cast of steel had once been made from pig iron containing 1 per cent. of sulphur and traces of manganese, and yet the sulphur was eliminated.

Mr. J. H. WHITELEY (Stockton-on-Tees) said the author had stated that the accepted view was that the phosphoric acid was present in molten basic slag as tetrphosphate of lime. For his own part, he did not accept that view, nor did he think the author had produced any sound argument in favour of it. For example, referring to Table I. of the paper, the author apparently considered that compound to be present because, after deducting the lime equivalent of the tetrphosphate and the base required for monosilicate from the total bases present, only a very small minus or plus quantity of base remained. He wished to point out, however, that if 3CaO were considered instead

of 4CaO as the base of the phosphate, say, in the first instance, K_3SO_4 , the residue of base would then become $+0.095$ instead of -0.04 . Further, the sum of the constituents given only amounted to about 92 per cent.; there was thus 7 per cent. or so to be accounted for, which he had no doubt was chiefly alumina. He thought it safe to assume that, in basic slags of the character shown, alumina would act as an acid, and if two molecules of base were allowed to one of alumina, 5 per cent. of Al_2O_3 would just about take up the $+0.095$ base obtained on the assumption that the tribasic phosphate was present. The same applied to all the examples given. In any case, the presence of appreciable amounts of alumina must certainly be considered in a calculation of that kind, which the author had not done, and for that reason he thought the author's argument in favour of the tetrabasic compound was of no value.

He (Mr. Whiteley) believed tribasic phosphate to be the compound generally present in the molten slag, for he had recently endeavoured to show, in a paper read before the Cleveland Institution of Engineers,¹ that when the basicities of slags in approximate equilibrium with the metal, as far as the phosphorus was concerned, were plotted against factors representing the distribution of phosphorus between slag and metal, a linear curve was obtained having its origin at a basicity of 2.0. The large number of slags thus examined had a fairly wide range of composition. The basicity was found by deducting the molecular equivalent of base required to form the tribasic phosphate from the molecular bases in the slag and dividing the remainder by the molecular equivalent of the silica, since only very small amounts of alumina were present. Factors representing the phosphorus distribution were obtained by dividing the percentage of phosphorus in the slag by that in the metal. None of the slags contained more than 12.0 per cent. of phosphorus, however, and while the points obtained by assuming the tetrabasic phosphate to be present instead of tribasic did not lie so close to the curve, its origin still appeared to be at 2.0. But this was not the case when the method was applied to a series of analyses of samples taken during the working of a basic charge recently given by Mr. Clements.² Here the phosphoric acid content of the slags was much higher, and yet points obtained by allowing for the presence of the tribasic phosphate, when plotted, gave a linear curve also having its origin at 2.0. But on the assumption that tetrabasic phosphate was present, no such curve could be obtained; in fact, the results were then not in agreement with those that he had found. For this reason, therefore, he considered that the phosphate contained in the molten slags described by the author was tribasic and not tetrabasic.

In Table II. the author gave the analyses of three basic slags containing no ferrous oxide. As far as he was aware, this was the first time that such results had been recorded, and in that respect they

¹ December 1922.

² *Journal of the Iron and Steel Institute*, 1922, No. I., Sheet No. 3.

were unique. Although there seemed to be no reason to doubt the possibility of obtaining a slag of that kind under the right conditions, yet information on one or two points was needed before accepting those results. Had the sample been taken simply by skimming the surface of the slag when little or no boil was proceeding? Also, had the possibility of the presence of a higher oxide of manganese than MnO in the slag been considered? That, if present, would cause ferrous salt to be oxidised in the process of analysis. He would like to know how the author accounted for the drop in the phosphorus content of the metal shown in the table, if a stable compound of lime and ferric oxide had formed, as was suggested. The evidence for the existence of that compound was very slender. He thought the explanation of the absence of ferrous oxide was rather to be found in the fact that the rate of reduction of the ferric oxide by the metal below to ferrous oxide was not sufficiently rapid under the existing conditions to counter-balance the combined actions of the oxidation of the ferrous oxide so formed by the furnace gases and its reduction by the phosphorus of the bath.

Professor T. TURNER (Birmingham) said he was largely in agreement with the author, in spite of the criticism in detail which had been made by Mr. Whiteley. It had been the custom to regard slags from a mineralogical point of view. He had a collection of crystalline slags, and after all, the slag which had had time to cool and to crystallise had not necessarily the same constitution as the material when fluid. He was inclined to think the author had spent more time than was necessary in the calculation of the atomic relationships. He regarded slags rather from the physico-chemical than the mineralogical point of view. It was not a question so much of the atomic ratios in the final slag as of the composition, the fluidity, and the temperature at the actual time of reaction between the metal and the slag.

He had in contemplation some experiments, which would be very difficult, no doubt, and perhaps might lead to nothing, but would have for their object the determination of the reactions of the slag by the electro-chemical method in the same way that the end of a reaction in a solution during electro-metric titration was determined. He thought that by a method of that sort an explanation of what occurred might be obtained and the actual reaction point between the fluid mixture of slag and the fluid metal determined.

The author, in his Conclusion 3, spoke of the basic oxides as merely passing into solution, and said the type of the compound was not altered. That was the view which he himself had put forward in 1891 in connection with the puddling process¹—that the fluid slag should be regarded, in the first place, as merely a neutral solvent. As the author had shown, that solvent contained certain active reagents—lime and oxide of iron in the present instance were the two

¹ *Journal of the Iron and Steel Institute*, 1891, No. I. p. 131.

important ones—and then it became a problem of the action of a reagent in the fluid state; in other words, a question of concentration of temperature. The author had plainly shown the effect of composition upon the rate of removal of phosphorus, and on those points he was in hearty agreement with him. He thought that what the author had said in reference to composition was entirely in accordance with experience, but he gathered that the author rather objected to the suggestion that temperature had any influence. It was obvious, in the first place, that a certain temperature was required to obtain fluidity; and, whether the extent of the influence of temperature had been accurately determined or not, its effect in such reactions must be important.

Take, for example, the reactions of sulphur in the blast-furnace—sulphur being taken up first, at a low temperature, by the iron, and afterwards, at a high temperature, by the lime. That was a question, not of the proportions of the constituents present, but of temperature. The effect of manganese, too, as Mr. Saniter had indicated, was largely affected by temperature. He thought that some modification or addition might be made by the author in the direction indicated.

The composition and high temperature reactions had not received sufficient attention. It was necessary to understand both the chemical and physical properties at high temperatures if the reactions which took place were to be explained. Until further knowledge was available, in addition to the valuable contribution which the author had made, what really took place would not be fully understood, even in processes so well known as the production of basic open-hearth steel.

CORRESPONDENCE.

Mr. J. E. FLETCHER (Dudley) wrote that all students of the fascinating problem of slag constituency would welcome the valuable contribution of the author. Tables I., III., IV., V., and VI., especially the four last, were invaluable, and gave reliable progressive analyses of the working slags during the working of the charge. It was incontestable that in studying those analyses the composition of the corresponding hearth metal should be available, and the author's conclusions deserved serious attention.

He (Mr. Fletcher) could not agree with the hypothesis advanced that the tetraphosphate was a safe basis for the rational constitution of molten basic slags. It was, of course, generally admitted that the bulk of such slags would be a phosphate of type $n\text{RO} \cdot \text{P}_2\text{O}_5$, but the value of n for molten slags had not yet been determined with certainty.

The method described was unquestionably based on sound principles and, in a similar series of analyses taken during the progress of puddling

operations, he (Mr. Fletcher) had endeavoured to arrive at the value of n in phosphates of $n(\text{FeO} \cdot \text{MnO}) (\text{P}_2\text{O}_5)$ type.

There was strong ground for the belief that those $n\text{RO} \cdot \text{P}_2\text{O}_5$ slags tended towards the inert condition (acid O = basic O) as expressed by $5\text{RO} \cdot \text{P}_2\text{O}_5$. That neutral condition was commonly attained in puddling slags where, considering Al_2O_3 and Fe_2O_3 as acid oxides, the ratio basic O per cent. acid O per cent. was unity.

It was generally agreed that the neutral silicate $2\text{RO} \cdot \text{SiO}_2$ was present, and that it was more stable than the $\text{RO} \cdot \text{SiO}_2$ form, which form, however, was probably the first to arrive, being the united product of the primarily released oxides from the metal—largely the result of furnace gas (oxygen-charged) action.

The mode of occurrence of Fe_2O_3 (and Al_2O_3) in the slags had always presented a difficulty, and the author's note on the possible presence of the constituent $x\text{CaO} \cdot \text{Fe}_2\text{O}_3$ in that connection was interesting. From an investigation of mill furnace cinder and soaking pit slags he (Mr. Fletcher) had occasionally found slags which approached very closely to the type represented by $3\text{FeO} \cdot \text{Fe}_2\text{O}_3$, which was, again, of neutral character.

Stead and Ridsdale's work on basic slags showed crystals which contained, as they estimated, the constituent $3\text{RO} \cdot \text{R}_2\text{O}_3$. It might prove, therefore, to be the case that in molten basic slags there was a tendency towards the formation of inert constituents of the type $3\text{RO}(\text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3)$. His own investigations on such slags during some years had been leading him to the view that, as the tendency of a basic working slag in both steel and puddling processes was towards the neutral or inert condition, the critical points alluded to by the author occurred when the slag approached that condition.

The production of the primary slags, before iron oxide addition, as the result of oxidation by the furnace gases, was certainly an important factor and largely fixed the composition of the first working slags—especially so when solid charges were being worked, and that could be specially noted when comparing slags (2) and (9) in Table VI. and (1) and (2) in Table IV. By abstracting the excess SiO_2 from the two latter the analyses became much more parallel in character, especially if the excess MnO in the slags of Table IV. were corrected for. A careful study of the slags in Tables IV. and VI. well repaid the trouble, as they furnished good examples of the way in which MnO and CaO replaced each other in, he believed, the $2\text{RO} \cdot \text{SiO}_2$ constituent. That phenomenon, as emphasised by the author, was all important, but the reduction of Mn back from the slag to the metal only occurred when the slag was acid—that was, when the acid oxygen content in P_2O_5 , SiO_2 , Al_2O_3 , and Fe_2O_3 was greater than the basic oxygen content in CaO , MgO , MnO , and FeO .

The contentions of Jüptner and Dichmann that the oxygen content was all important were proven, and, in the writer's view, if the slags

were considered as consisting of the three neutral constituents $5\text{RO} \cdot \text{P}_2\text{O}_5$, $2\text{RO} \cdot \text{SiO}_2$, and $3\text{RO}(\text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3)$, with free SiO_2 if acid and $\text{RO} - (\text{FeO} \text{ or } \text{CaO})$ if basic, in solution, that important oxygen function could be readily demonstrated by graphing the oxygen contents of the slags. To illustrate that the writer had prepared certain diagrams. The upper graphs showed the alterations in the slag compositions (oxygen contents), taking the writer's hypothesis as basis. The lower graphs similarly indicated the oxygen distribution on the author's basis.

It was clearly demonstrated in the upper graphs that :

- (1) The basic open-hearth slags were probably composed of the three neutral constituents, A, B, and C, with or without free SiO_2 or free RO in solution.
- (2) If free acid oxygen were present (in SiO_2), MnO was reduced, Mn passing back into the metal.
- (3) If free basic oxygen were present (in FeO , MnO , or CaO), neither rephosphorisation nor Mn reduction from MnO occurred.
- (4) When slags became neutral (point R on graphs) the elimination of carbon, manganese, and phosphorus was generally retarded, but was speeded up again as the slags became more basic.
- (5) The increase of basicity was accompanied by an increase in the $2\text{RO} \cdot \text{SiO}_2$ content. There appeared to be an equilibrium reached where the sum of the

$$2\text{RO} \cdot \text{SiO}_2 \text{ and } 3\text{RO} (\text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3)$$
oxygen contents remained constant.
- (6) When there was sufficient CaO to form $5\text{CaO} \cdot \text{P}_2\text{O}_5$ carbon was eliminated, but was retarded when the slag became neutral.
- (7) The total basic oxygen content in the neutral constituents $5\text{RO} \cdot \text{P}_2\text{O}_5$, $2\text{RO} \cdot \text{SiO}_2$, and $3\text{RO} \cdot \text{R}_2\text{O}_3$ was a critical function and influenced the rate of phosphorus elimination from the metal in direct proportion to the percentage of acid oxygen present in the $5\text{RO} \cdot \text{P}_2\text{O}_5$ and $2\text{RO} \cdot \text{SiO}_2$ constituents. That bore out H. H. Campbell's discovery that the sum of the SiO_2 and P_2O_5 percentages in basic open-hearth slags governed the rephosphorisation of the metal. Expressed in oxygen contents Campbell's results were :

In 5 % P_2O_5 slags	the oxygen content in $\text{SiO}_2 + \text{P}_2\text{O}_5$ should not exceed					13.5 %
In 10 %	"	"	"	"	"	15.0 %
In 15 %	"	"	"	"	"	16.5 %
In 20 %	"	"	"	"	"	17.5 %

If the total acid and basic oxygen content in the three neutral constituents exceeded the above values rephosphorisation occurred. To avoid that the slags should contain excess RO additions (CaO). It would appear that the $5\text{RO} \cdot \text{P}_2\text{O}_5$ and $2\text{RO} \cdot \text{SiO}_2$ constituents were very unstable

when the acid oxygen contents corresponded with Campbell's limiting values and were then sensitive to either RO or SiO_2 additions.

- (8) The diagrams marked A and B (Fig. 1), showing a number of neutral basic slags investigated by Scott and McArthur,¹ A depicting the usual analyses and B the constitutional analyses, showed the distribution of the suggested neutral constituents in slags of increasing P_2O_5 content.

The lower graphs did not emphasise the suggestions brought out in the upper ones, and left some doubt concerning the function of the oxygen in the 2RO SiO_2 and remaining portion of the slag. By separating the oxygen content in the Al_2O_3 and Fe_2O_3 (see areas marked G) the oxygen content in the remaining RO oxides was shown in areas marked F, which suggested the speed of the basicity change but indicated no free silica in any of the slags, the whole of the silica being combined with basic oxides in the form of the silicate 2RO SiO_2 . The author's analyses did not give the alumina content, but that has been taken to constitute the balance.

Another point which had interested him when preparing the diagrams was the interchange of RO oxides which must be continually taking place during the working of a charge, between the two constituents 2RO SiO_2 and $3\text{RO R}_2\text{O}_3$. When CaO, for instance, replaced or displaced FeO or MnO there would be a volumetric change accompanied by either endothermic or exothermic action. The author had referred to certain heat evolutions when the primary oxides were formed, P_2O_5 , MnO, &c., but other heat evolutions occurred when the silicates, aluminates, phosphates, and ferrates were formed, and those would be associated with volume changes.

If, as was probable, there was a relationship between the atomic formula weight of a silicate and its density, an exchange between say 2FeO SiO_2 and 2CaO SiO_2 would be associated with a change in volume and density of the slag.

It was possible by graphing the changes occurring in the contents of the neutral constituents to visualise those volumetric changes, and some light was thereby thrown on the observed volume changes in the slag occurring throughout the basic steel and puddling processes. Those changes, if studied from the point of view of heat exchanges, might lead to a better understanding of the velocity of diffusion and of viscosity in slags, the importance of which had been already pointed out by H. H. Campbell, Wilson, and others, as seriously affecting the speed and efficiency of the interreactions in the slags themselves and between the active slag oxides and the metal. Such phenomena could only be studied by those who, like the author, could in actual practice bring the spirit of true research to bear on such a complex problem as that of the molten constituency of working slags.

¹ *West of Scotland Iron and Steel Institute, 1921-2.*

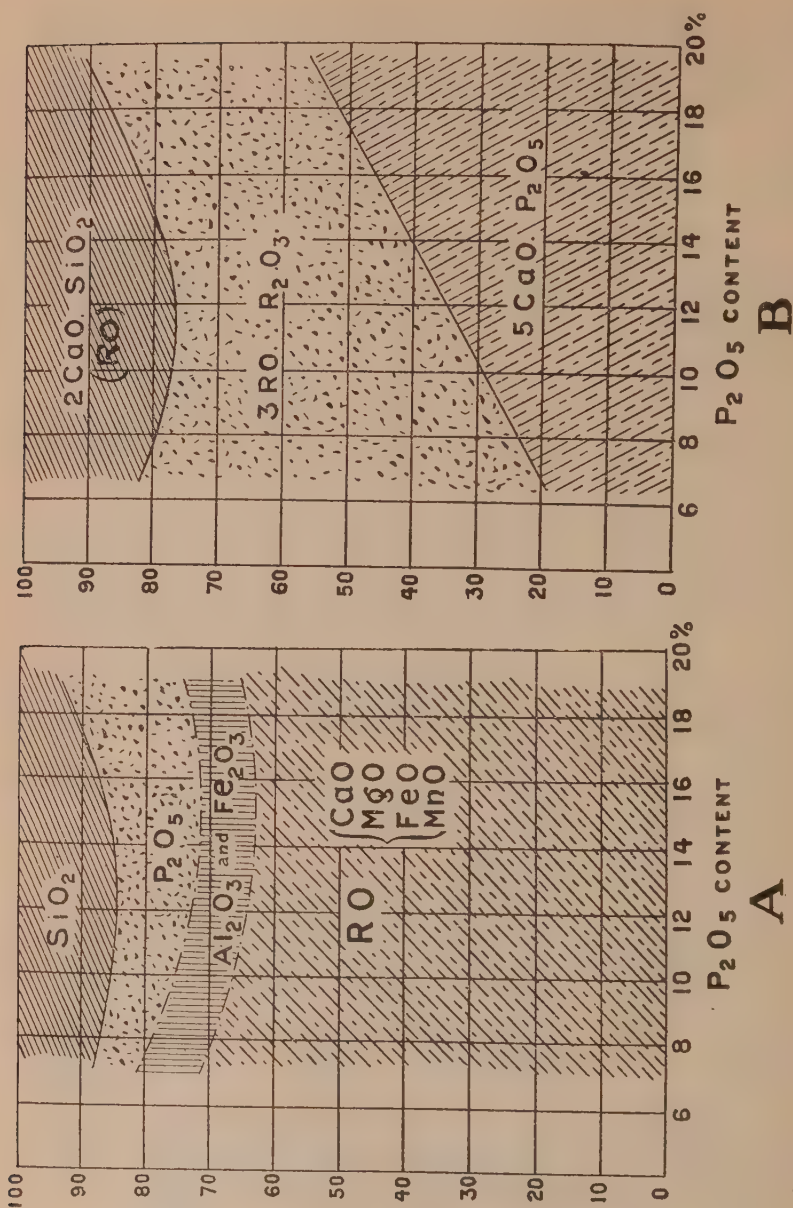


FIG. 1.

Dr. F. C. THOMPSON (Manchester) wrote that Mr. Colclough's paper was an important contribution to the chemistry of the basic open-hearth. Taken as a whole it appeared to him that Mr. Colclough had substantiated his conclusions, and though it might be that in detail slight modification might be required, there was little doubt that the main features of the work would stand. The paper had modified generally accepted views appreciably, and in particular the fact that slag composition was the dominating factor in the process and that thermo-chemical effects were subsidiary to that marked a most important step. It had been fairly generally accepted in the past that the thermal aspects of the chemistry of the process were of very much greater importance than the author had shown to be the case. For the first time the real cause of the variations in the relative rates of oxidation of carbon and phosphorus was made clear, and the whole question of the chemistry of their removal was raised to a higher plane. Mr. Colclough's views on the effect of manganese on sulphur were of considerable interest, and in making the manganese adopt a practically catalytic rôle, certain hitherto unexplained results might become understandable.

Mr. J. F. WILSON (Motherwell) agreed with Mr. Colclough in that stable or inert slags could be formed in basic open-hearth furnaces, which were essentially tetrabasic phosphates of lime and monosilicate. That definite compound provided a basis from which slag research might be simplified. Had the author made his furnace-charging arrangements such that the production of the inert slag was approached in the latest stages by the simultaneous reduction from the slag of both iron oxide and phosphoric acid, the calculated slag composition $x(\text{Ca}_4\text{P}_2\text{O}_9) + y(\text{R}_2\text{SiO}_4)$ would have been more minutely correct; and moreover, that to obtain that formula correct without an excess of bases, it would have been found necessary to include the iron oxides as combined bases. Examples of a large number of inert slags made in the manner indicated above had been published.¹

The stable slags given by Mr. Colclough were comparable to those produced in the first period of the Hoesch process, and his (Mr. Wilson's) experience with similar slags had been that the approach to the saturated composition gave a slow oxidation of phosphorus from metal to slag with a slag composition a little more basic than the formula $x(\text{Ca}_4\text{P}_2\text{O}_9) + y(\text{R}_2\text{SiO}_4)$ allowed for, and that that excess of base persisted. In his opinion that incomplete saturation was owing to the feeble dephosphorising ability of the almost saturated slag low in iron oxide, whereas by approaching the inert slag composition by the reduction of phosphoric acid in the manner stated above, the $x(\text{Ca}_4\text{P}_2\text{O}_9) + y(\text{R}_2\text{SiO}_4)$ composition was readily reached. A study of that double reduction of iron oxide and phosphoric acid in the presence of high

¹ Wilson, *Journal of the Iron and Steel Institute*, 1920, No. I. p. 273, Slags Nos. 5 and 6.

percentages of reducing agents in the metal proved that the iron oxides were in the combined state, and that their presence in the free state due to the progressive oxidising influence of the flame was restricted to the time lag in their rate of combination. In fluid slags containing low percentages of iron oxides he thought that time lag might be safely ignored. To add iron oxide to a saturated slag in the presence of high percentages of reducing agents in the metal, did not necessarily prove that, because that oxide was quickly reduced, it must have been in the free state. Rather should it be stated that it was the basic oxide most easily reduced from combination with the slag. The sequence in which the different oxides and metalloids were reduced or oxidised chiefly depended on thermo-chemical considerations, although it must necessarily follow that, particularly in the case of acid oxides, slag basicity must be a very important factor.

The writer did not agree with the author's statement as to the manganese silicate being unstable in the presence of free lime. Since FeO was more easily reduced than MnO , the reduction of the latter depended largely on the relative concentration of the two oxides in the slag, and the reducing agents present. That reduction of MnO was fairly common even in cases where the question of free lime did not arise, Table IV. might almost be cited as an instance.

In the author's discussion (p. 272) on the "Effect of Slag Composition on Rate of Elimination of Metalloids," a quotation was extracted from a discussion on the "Influence of Slag Condition on Elimination of Metalloids"; no useful purpose could be served by taking the composition of a slag as meaning the same thing as the condition. It would appear (p. 275) that the author had not completely apprehended the position taken in relation to the existence of bisilicates in some slags, as it had never been contended by him (Mr. Wilson) that bisilicate existed in such slags as the author cited, but on the contrary¹ in slags much more siliceous.

Mr. B. YANESKE (Sheffield) wrote that it appeared to be an established fact that the molten slag in either an acid or basic furnace was constantly attempting to acquire and maintain a condition of equilibrium, that was, to adhere to a definite molecular composition, and to attain that it would attack the furnace hearth, the elements in the metal or additions made to the bath depending upon its immediate requirements, so that the removal of the elements depended primarily upon the composition of the slag. Therefore, he agreed with Mr. Colclough that Mr. Wilson's statement¹ that the composition of the slag had little or no effect upon the relative rates of oxidation of carbon and phosphorus, was not in accordance with practice. When the slag attained the state of equilibrium it became quiescent, and the slags investigated by Mr. Colclough must have been in approximately that condition for them to conform so closely to the definite

¹ *Journal of the Iron and Steel Institute*, 1920, No. I. p. 281.

composition, 4CaO , P_2O_5 , 2RO , SiO_2 . It was also interesting to note that the slags referred to by Mr. Wilson¹ also approximately conformed to that formula.

Whilst he appreciated Mr. Colclough's paper, he would have found it more useful if he had supplied more data relating to the obtainment of his series of slags, such as weight of charge, proportion and composition of scrap and hot metal used, and weight of limestone added for each slag, and how long after melting the desired slag was obtained. He thought the author's statement that manganese silicate was unstable in the presence of excess lime was correct, and in practice had frequently observed that silica had a greater chemical affinity for CaO than for MnO .

Mr. COLCLOUGH wrote that Mr. Saniter urged the claims of iron oxide to rank as a strong base in the removal of phosphorus. Under certain conditions that was possible, but such conditions were unstable, and unless lime was added quickly the phosphoric oxide was reduced again, and the phosphorus returned to the metal.

With reference to the desulphurising action of manganese, Mr. Saniter claimed that manganese sulphide could exist in the liquid steel, because sulphide segregations in ingots did not contain manganese and sulphur in atomic proportions. It was commonly accepted that the sulphide particles in steel were not pure MnS but a complex $x\text{FeS}, y\text{MnS}$. It was therefore not surprising to find that there was no atomic relation between the manganese and sulphur. Further, the reaction



probably never proceeded to completion, but to an equilibrium stage with MnS and FeS co-existent in the liquid steel.

Importance was attached to the action of manganese, because, as stated in the paper, sulphur was always removed when either manganese was added to the bath in the absence of a highly oxidising slag, or the conditions were such as to cause the reduction of MnO from the slag to manganese passing into the bath. The constant association of the two processes could not be accidental, and the pseudo-catalytic action of the manganese seemed clear. It might be added that, although the manganese in the pig iron used in the tests exceeded 1 per cent., the same results were obtained with pig iron of 0.6 per cent. manganese, yielding about 0.3 to 0.4 per cent. manganese in the bath at melting.

Mr. Whiteley made strong criticism of the view that the phosphorus was present in the slag as the tetra-calcic phosphate. It was quite correct that in the slags of Table I., assuming that (1) the tri-calcic and not the tetra-calcic phosphate was formed, and (2) the alumina acted as an acid and formed a compound $2\text{CaO}, \text{Al}_2\text{O}_3$, the

¹ *Journal of the Iron and Steel Institute*, 1920, No. I. p. 274.

excess of bases approached even more nearly to zero than those in the table. Those two assumptions are, however, open to criticism.

In the first place, slags which experience showed to be on the borderland between excess base and acid, formed, on cooling, crystals of the tetra-calcic salt. In the absence of excess lime, it was difficult to see where the lime was to come from—during cooling—to change the liquid tri-calcic phosphate into crystalline tetra-calcic phosphate. It seemed reasonable, therefore, to assume that in such slags the tetra-basic compound was formed in the molten slag.

In the paper no reference was made to alumina, so as to concentrate attention on the constituents CaO , SiO_2 , and P_2O_5 . In the conditions prevailing it was probable that alumina did not act as either a definite acid or base. In the first place, there was no evidence of a compound $2\text{CaO}, \text{Al}_2\text{O}_3$; Rankin and Shepherd had shown that the highly basic compounds formed by CaO and Al_2O_3 are $3\text{CaO}, \text{Al}_2\text{O}_3$ and $5\text{CaO}, 3\text{Al}_2\text{O}_3$. Again, it was not the binary system, $\text{CaO}-\text{Al}_2\text{O}_3$, but the ternary system, $\text{CaO}-\text{SiO}_2-\text{Al}_2\text{O}_3$, which had to be considered.

It was generally accepted that the silica present exists as the monosilicate, say $2\text{CaO}, \text{SiO}_2$. Rankin, Day, and Shepherd,¹ in their diagram of the ternary system, showed that the three oxides formed a compound $2\text{CaO}, \text{Al}_2\text{O}_3, \text{SiO}_2$, and that for low percentages of alumina, such as were present in the slags under consideration, there was a continuous series of mixtures or solutions of $2\text{CaO}, \text{SiO}_2$ and that compound $2\text{CaO}, \text{Al}_2\text{O}_3, \text{SiO}_2$. That was, in the melts formed, (a) there was no trace of any separate compound $x\text{CaO}, y\text{Al}_2\text{O}_3$, and (b) the relation between CaO and SiO_2 throughout was 2 : 1 and was unaffected by the alumina present.

The alumina, in that range of compositions, followed its usual amphoteric properties and made no claim on the free lime. There was, therefore, sufficient lime in the slags to form the tetra-calcic phosphate as suggested in the paper.

On those grounds the consideration of alumina was omitted from the paper, so as to avoid confusing the issue. Thanks were due to Mr. Whiteley for his criticism, which enabled the point to be made clear.

The examples given in Table II. of slags free from, or very low in, ferrous oxide were certainly unique, and had not been observed except in the special conditions prevailing when the samples were taken. The samples were representative of the slag present and, as the table showed, were taken at a period when there was no carbon "boil." There was no evidence of the existence of higher oxides of manganese than MnO ; on the contrary, at that period the MnO of the slag was being reduced to manganese. The fall in the phosphorus content was due to the constant oxidising effect of the furnace gases, and the oxidising of the MnO of the slag.

In reply to Mr. Wilson it might be pointed out that in Table IV.

¹ *American Journal of Science*, vol. xxxiv.

an example was given where oxide of iron and oxide of phosphorus were reduced simultaneously two and a half to three hours after melting. The composition of the slag at sample 5, during that operation, coincided exactly with the formula $x2\text{RO}, \text{SiO}_2$ with $y4\text{CaO}.\text{P}_2\text{O}_5$, but the inclusion of oxide of iron as base in that was not necessary. His criticism as to the instability or otherwise of manganese silicate in the presence of free lime was adequately dealt with in the contributions of Messrs. Fletcher and Yaneske, for whose confirmation on that point thanks were due.

It was to be regretted that in the effort to avoid undue length in the paper the details asked for by Mr. Yaneske could not be furnished. The contribution of Mr. Fletcher was especially interesting, coming from one who had devoted so much time and study to the subject. His confirmation of several of the points raised was fully appreciated, but exception had to be taken to some of his suggestions. In view of the action of sand quoted in the paper, it was most difficult to conceive the presence of free silica in a slag. The example given showed that the addition of silica at once liberated the equivalent amount of phosphoric acid, which was then reduced to phosphorus. The same remarks applied to the reduction of manganous oxide; the data given showed that free "acid" oxides did not exist in a stable slag, the reduction of manganous oxide usually occurred when the slag was high in free bases and low in oxide of iron. Mr. Fletcher's attention was drawn to the criticism of Mr. Whiteley's theory with regard to alumina given above.

Thanks were due to Professor Thompson for his appreciative remarks. As he pointed out, the main objects of the paper were to modify the accepted view that thermo-chemical considerations were *the* deciding factors in studying furnace reactions, and to direct attention to the profound effect of slag composition, alone, on the reactions produced.

Iron and Steel Institute.

THE CONSTITUTION OF THE ALLOYS OF
IRON AND NICKEL.

By D. HANSON, D.Sc. (THE NATIONAL PHYSICAL LABORATORY), AND
J. R. FREEMAN, JUN. (THE UNITED STATES BUREAU OF STANDARDS).

INTRODUCTION.

THE research described in the present paper has been undertaken at the National Physical Laboratory, and is a continuation of the investigation carried out by D. Hanson and Hilda E. Hanson,¹ in which the constitution of the nickel-iron alloys at temperatures below 900° C. was determined. The present authors have extended this work by determining the constitution of the alloys up to their melting points.

The only previous investigation of this kind is that of Guertler and Tammann,² who determined the freezing-point curve. The $\delta \rightarrow \gamma$ transformation, then undiscovered, does not appear in their equilibrium diagram. A further determination of the constitution, using the purest available iron and nickel, therefore appeared necessary.

PREPARATION OF THE ALLOYS.

The alloys were prepared by melting together Armeo iron and Mond nickel shot. The composition of the iron was as follows :

	Per Cent.
Carbon	0.012
Silicon	0.017
Sulphur	0.017
Phosphorus	0.014
Manganese	0.07

The nickel contained 99.98 per cent. nickel.

The greatest difficulty in preparing the alloys consisted in keeping them free from carbon. The melts were made in a "carbon-ring" furnace, and, in order to prevent contamination

¹ Hanson and Hanson, "The Constitution of the Iron-Nickel Alloys," *Journal of the Iron and Steel Institute*, 1920, No. II. p. 39.

² Guertler and Tammann, *Zeitschrift für anorganische Chemie*, 1905.

by carbon, it was necessary to enclose the crucible in a refractory muffle. For this purpose, muffles made of a mixture of china clay with 10 per cent. of alumina were used: the authors are indebted to Mr. V. H. Stott, M.Sc., for the preparation of these muffles. Purified nitrogen was passed into the muffle to prevent oxidation of the melt. Crucibles made from fused alumina were used. The iron and nickel, previously carefully washed clean and free from grease, were melted together in the crucible to form 50-gramme melts. No stirring was required, as it was found that the ingots were quite homogeneous after they had become solid, and drillings taken from top and bottom had the same composition. The analyses of the alloys used are given in Table I.

TABLE I.—*Compositions of Alloys and Arrest Points.*

Reference No.	Composition.	Arrests on Cooling Curve.	
	Nickel per Cent.	Freezing Point.	Second Arrest.
Pure iron	...	1530	1400
FN 1	1.14	1525	1444
2	1.98	1524	1468
3	2.89	1518	1494
4	3.74	1517	1501
5	5.09	1502	...
6	5.80	1502	...
8	8.02	1498	...
10	9.96	1493	...
15	14.6	1490	...
25	24.7	1471	...
35	34.8	1457	...
45	45.1	1446	...
55	54.6	1440	...
60	59.3	1439	1434
65	65.1	1436	1432
67.5	66.7	1436	...
70	69.3	1436	1431
75	74.5	1437	1433
80	79.2	1442	...
85	84.2	1444	...
90	89.1	1450	...
Pure nickel	...	1452	...

THERMAL CURVES.

The taking of thermal curves of alloys melting at a temperature above 1500° C. is very difficult, since it is not easy to

measure these temperatures with sufficient accuracy. Platinum-rhodium thermocouples can, if suitably supported and protected, be used at these temperatures, but they rapidly deteriorate with use, and must be examined very frequently if reliable results are to be obtained. This deterioration is due to a variety of causes, which cannot now be discussed fully; contamination by gases, derived from the furnace or melt, is very severe, unless adequate protection is afforded, and failures frequently occurred through cracking of the refractory thermocouple sheath, when the gas from the muffle or furnace rapidly attacked the wire, rendering it brittle. Even when the failure of the sheath did not occur the thermocouple rapidly changed in the neighbourhood of the junction, which was hottest, and temperature readings became unreliable. This was, no doubt, partly due to the fact that the refractory sheath was not completely impervious to injurious gases, but no doubt also due to the elevated temperature alone, since exposure to temperatures over 1500°C . for any considerable time, even in the absence of foreign injurious gases, is harmful, and produces an alteration in the thermal electromotive force of the element, probably as a result of volatilisation of rhodium. It was found that reliable results were obtained only if the thermocouple was exposed to a very high temperature for a short time; heating curves could not be obtained in addition to cooling curves, since they involved an exposure of the couple to a high temperature for too long a time, and cooling curves only have been taken.

The apparatus used is illustrated diagrammatically in Fig. 1. The procedure finally adopted was as follows. The metals were melted together in the crucible C, contained in the muffle M, which was inserted in the "carbon-ring" furnace. The muffle was provided with a stopper K, in which were drilled three holes—one (N) to lead in the nitrogen gas; another, covered by a mica cap, H, as an inspection window; and a third, in the centre, through which the thermocouple could be inserted; this last hole was closed by means of a stopper during the melting of the alloy. After the crucible and metal had been inserted the stopper was luted into the muffle, and the air replaced by nitrogen; the muffle was heated slowly until the metal melted, the time taken being approximately one hour. The course of

this operation could be watched through the mica window, and the moment of complete melting could easily be ascertained. After the metal had been molten about five minutes, which was found to be sufficient to secure complete mixing, the thermocouple, encased in a long fireclay sheath, closed at one end, was inserted through the central hole in the lid and lowered into the melt, in which it was placed as near the centre as possible :

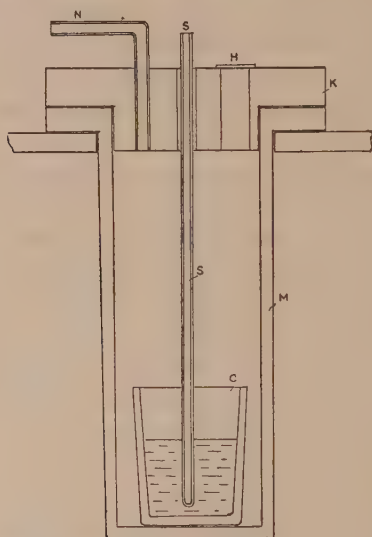
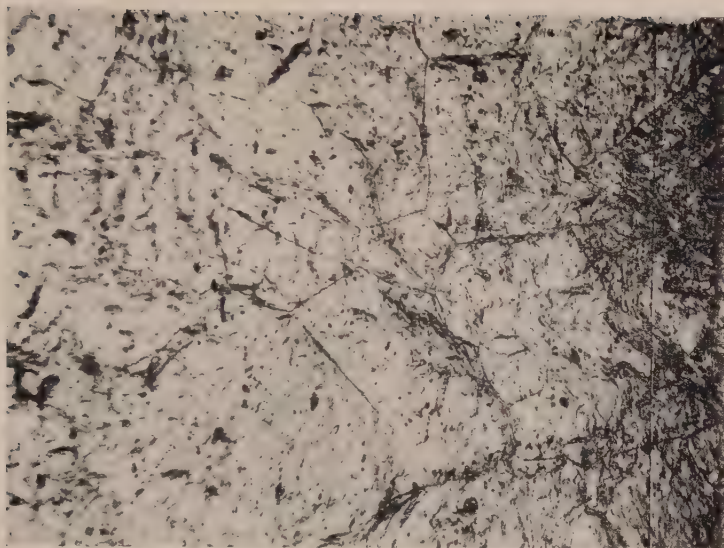


FIG. 1.

this was fairly easily done, since it was possible to see the position of the sheath through the mica window, H. The sheath and thermocouple were not placed in the melt unless it was ascertained, by reading the temperature of the junction as it was lowered into the furnace, that the temperature was not unnecessarily hot. If this were found to be the case, the sheath was withdrawn and the temperature lowered. As soon as the thermocouple was in place, the current supplying the furnace was reduced, and the cooling curve taken immediately. By this procedure the thermocouple was exposed to an injurious temperature for the minimum time.



No. 1.

× 50.

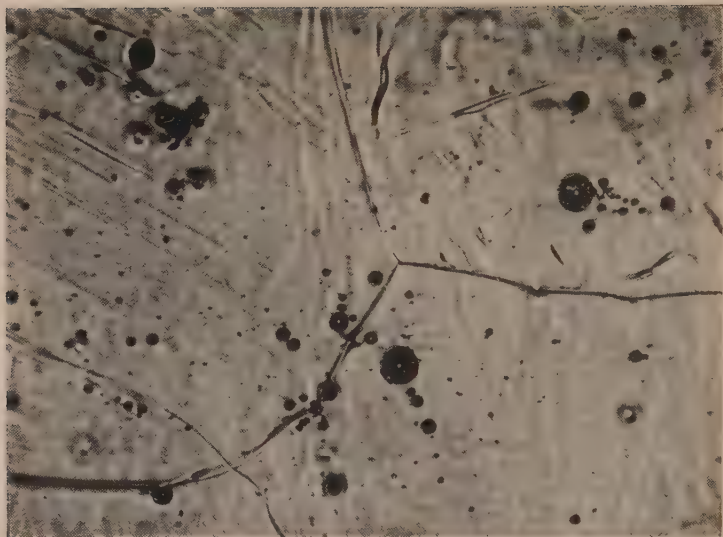
1% Nickel-iron, heated for 2 hours at 1300° C. in nitrogen and cooled quickly. Heat etched.



No. 2.

× 50.

1% Nickel-iron, heated for 2 hours at 1300° C., raised to 1450° C. during 14 minutes and cooled quickly. Heat etched.



No. 3.

×150.

Same as No. 1: showing surface markings that appear to change direction at crystal boundaries.



No. 4.

×150.

Same as No. 2: showing surface markings unrelated to crystal boundaries.

Most of the alloys undercooled slightly through their freezing points; in some cases this undercooling was considerable—over 30°C .—and rendered the results unreliable. The difficulty was overcome by inoculating the melt by means of sawdust of iron or nickel for the pure metals, or of a mixture of the two for the alloys. This metallic dust was dropped into the muffle between the thermocouple sheath S and the side of the central hole in the stopper, where a slight gap existed. In this way all undercooling at the liquidus was prevented.

The thermocouple used in the research was calibrated, in the first place, against the standard of the heat division of the National Physical Laboratory, and checked, when necessary, by redetermining the melting point of pure nickel. For the alloys rich in iron, possessing the highest melting points of the series, it was usually necessary to cut 1 to 2 inches of wire from the end of the thermocouple after each thermal curve, but for the alloys containing 35 to 100 per cent. nickel a couple would last for several melts; the maximum number of curves taken with one junction was six, after which it was found to read 2°C . low, and a fresh junction was prepared. The authors have endeavoured to keep errors in temperature measurement, due to couple contamination, less than 2°C ., and any junction in which an error greater than this was found has been discarded. Moreover, when the authors' results were plotted in the form of an equilibrium diagram, any point which fell more than 2°C . from the mean curve was redetermined, and was always found to be in error. The freezing points of some of the alloys have had to be determined several times (in two cases five times each) before agreement could be obtained. If, however, the *highest* freezing temperature for each alloy is plotted against composition, no point lies more than 2°C . from the mean curve running through them. In some cases, when the thermocouple had become seriously contaminated, the indicated melting point was 20°C . from this mean curve. It is thought, therefore, that the errors in the equilibrium diagram, due to thermocouple defects, are negligible. An error of 2°C . is not greater than might be obtained from a variety of other causes in experiments of this kind, carried out at such a high temperature.

The results of thermal analysis are given in Table I.

EQUILIBRIUM DIAGRAM.

The equilibrium diagram, in the region now investigated, is shown in Fig. 2. This diagram has been plotted from the results of the thermal curves alone, but is confirmed by microscopic examination of the alloys.

The portion of the diagram referring to the iron-rich alloys containing 0 to 10 per cent. of nickel is shown, on a larger scale, in Fig. 3.

IRON-NICKEL ALLOYS

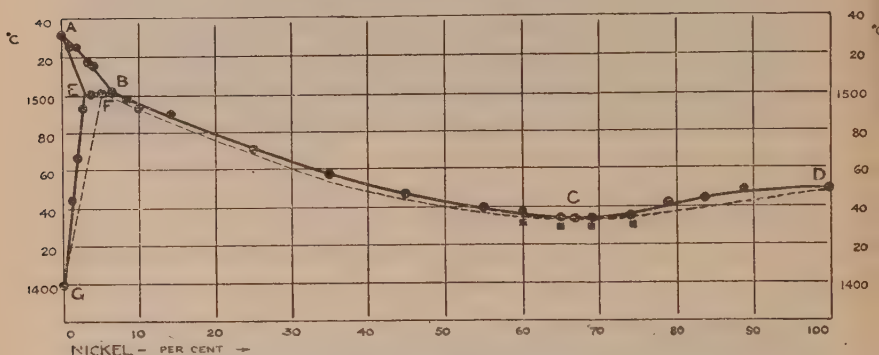


FIG. 2.

Freezing of the alloys begins at temperatures indicated in Fig. 2 by the line ABCD: over the range between A and B, δ -iron separates from the liquid; between concentrations represented by the point B and pure nickel (point D) the alloys consist, when just solid, of a continuous series of solid solutions. The freezing-point curve over this range has a minimum at the point C, at a concentration of approximately 65 to 70 per cent. of nickel. The exact meaning of this minimum in the freezing-point curve will be discussed later.

The iron-rich alloys between the compositions of the points A and B undergo a transformation below the liquidus, at which the δ -iron first formed changes into γ -iron. This transformation is represented by the broken line GEB: the portion GE may be regarded as representing the raising of the δ - γ transformation temperature of pure iron by the addition of nickel.

The effect due to nickel is very profound, and an addition of only 3 per cent. raises the transformation point 100°C . The point E represents the point of maximum solubility of nickel in δ -iron, and along the line EB δ -iron of this composition reacts with liquid of the composition represented by B to form γ -iron of the composition represented by F; nickel is more soluble in γ -iron than in δ -iron. It must be pointed out that the position of the point F has not been determined experimentally, and all

NICKEL-IRON ALLOYS

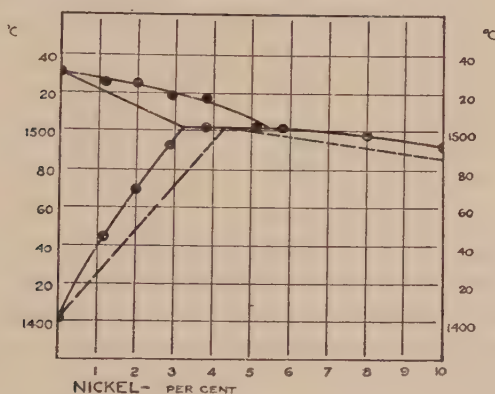


FIG. 3.

that can be said is that it lies somewhere between the points E and B.

The solidus of the system, the line AEFCD, has not been determined by experiment, and is shown dotted. It is, however, very close to the liquidus line, especially over the region between the point B and D; over this range of composition all the alloys have very sharp freezing points very similar to those of pure substances, and it is evident that the temperature range between liquidus and solidus is very small.

The exact constitution of the alloy represented by the point C is not very clear. The composition is very close to that of the chemical compound FeNi_2 , and it might have been supposed that the alloy consists essentially of this chemical compound, particularly as, at a lower temperature, another transformation

occurs in the alloys of this system which has a maximum reaction temperature in an alloy of approximately the same composition. In order to obtain some further evidence bearing on this point, a series of hardness tests was made on alloys whose compositions lay on either side of the point C, and the results of those tests are shown in Table II. and in Fig. 4.

TABLE II.

Alloy.	Scleroscope Hardness.	
	As Quenched from 750° C.	Slowly Cooled to Room Temperature.
FN 60	21.0	17.0
65	18.0	18.0
67.5	18.5	17.5
70	18.0	18.0
75	17.0	17.5
80	17.0	16.5

The values given are means of five readings. In no case was the deviation of any reading from the mean value greater than 1.

It is seen that the hardness of the specimens quenched between the upper and lower transformation of the system lies on a continuous curve and shows no discontinuity in the neighbourhood of the composition of the alloy C. The same is found in the case of alloys that have been slowly cooled through the lower transformation point. If the alloy C consisted of the compound FeNi_2 , either between the melting point and the lower transformation temperature, or below the lower transformation temperature, it would have been anticipated that a discontinuity, or rather, a minimum, would be found in the hardness-composition curve, at the concentration of that compound. It is also of interest to note that the alloy of this composition is relatively soft and ductile and does not possess the great brittleness that is so frequently associated with intermetallic compounds. In order to settle this question finally, it will probably be necessary to examine other physical properties of the alloys of this series.

The microstructures of the alloys containing 5 to 100 per cent. of nickel suggest that they have all consisted immediately

after solidification of a single constituent. Whether quenched or cooled slowly the alloys possess the simple structure of a single solid solution.

The form of the liquidus curve suggested that the alloys might possibly form two solutions over a short range of composition near 70 per cent. of nickel. The liquidus curve is very flat in this region, and a short eutectic line might easily escape notice. The cooling curves of these alloys were therefore taken with very great care, observations of the rate of cooling being taken every 1°C . instead of every 3°C ., which was the interval usually adopted. In the alloys containing 60, 65, 70, and 75 per cent. nickel a small second arrest point

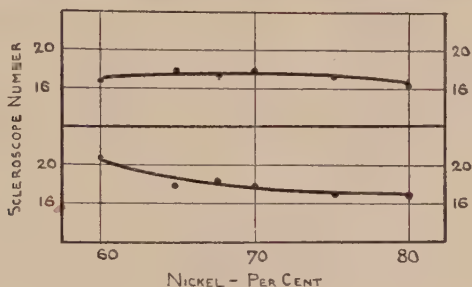


FIG. 4.

was observed at a temperature of 1432° to 1434°C ., and this arrest point is indicated on Fig. 2. In each case a slight recalescence, about half of one degree centigrade, was noticed, so that the observed temperatures are a little lower than the "equilibrium" transformation points. In no case, however, is this small second arrest point more than 5°C . below the liquidus. The cooling curve of the alloy containing 67.5 per cent. of nickel gave a very slight indication of a second "arrest" at a rather lower temperature (1428°C .), but this was much smaller than that found in the case of the other alloys, and was too indefinite to be considered a definite "arrest" point.

The occurrence of a second arrest of this kind may indicate the presence of a eutectic, stable or metastable, or may merely be due to cooling too rapidly for equilibrium in regard to chemical composition to be maintained during the process of solidification.

In the present instance the very small character of the arrest point in all the alloys in which it is found suggests that the latter explanation is the correct one, and that the alloys consist entirely of solid solutions and are not eutectiferous, even if cooled relatively rapidly. The absence of a second arrest in the alloy containing 67.5 per cent. of nickel suggests that this alloy lies very close to the minimum of the freezing-point curve. The occurrence of a second arrest point on either side of this minimum would be expected if the rate of cooling were not slow, as a result of the normal process of freezing in such a case. Fig. 5 illustrates this. The curves ABC and DBE represent respectively the liquidus and solidus of such a system, which consists of a

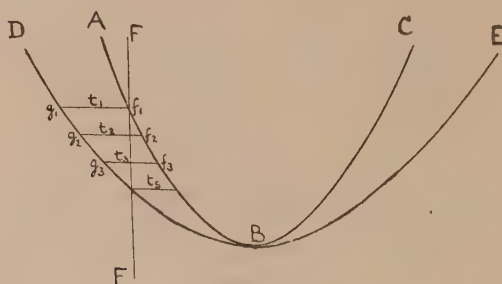


FIG. 5.

continuous series of solid solutions, whose freezing-point curve falls to a minimum at B. An alloy F, near this minimum, begins to freeze at the temperature t_1 , by depositing crystals of composition g_1 . If equilibrium between the solid and liquid phases is maintained by slow cooling, the compositions of the phases are represented at the temperatures t_2, t_3 by g_2, g_3 , for the solid, and f_2, f_3 for the liquid phase, while at t_4 the whole alloy is just solid and has the uniform composition F. If, however, the rate of cooling is not very slow, "cored" crystals are formed, and the freezing range of the alloy is extended, and the temperature of the minimum point may be reached before solidification is complete, at which temperature the composition of the remaining liquid is represented by B. If, when this temperature is reached, an appreciable quantity of liquid alloy remains unfrozen, as is manifestly possible with rapid rates of cooling, an arrest

point must occur, since liquid of this composition has a definite freezing point, the solid and liquid phases having the same composition. In taking a cooling curve the rate of cooling is seldom, if ever, sufficiently slow to prevent "coring" of the solid solution, and the conditions are therefore favourable for the production of spurious arrest points of the kind indicated.

In order to verify further the above conclusions, an alloy containing 65 per cent. of nickel was remelted, allowed to solidify at a moderate rate (about cooling curve rate), and quenched from a few degrees below its solidification point. If the system were eutectiferous, it was anticipated that two phases would be present in the alloy after this treatment; if the system was one consisting, when in equilibrium, of only one phase, two phases could not be formed under any conditions of rapid cooling. Microscopic examination showed that the quenched sample consisted of one solid solution, and indicated that the diagram was of the type illustrated in micrograph No. 1 (Plate XIV.).

DELTA IRON.

An attempt was made to show, by means of the microscope, that δ -iron, and the δ -iron phase, differed from the γ -iron phase, and that the change from one to the other was accompanied by a recrystallisation of the material. The transformations in iron and iron-nickel alloys take place with such rapidity on cooling, that it is impossible to preserve, by quenching, the δ - and γ -modifications. Attempts were therefore made to preserve the structures existing at high temperatures by the "vacuum etching" of polished surfaces, previously prepared. Specimens of iron were polished and heated in a porcelain tube to temperatures above and below the δ - γ transformation point, but no clear indications were obtained of the structures that existed at the high temperature. The surface markings on the specimens after this treatment were very complex; iron that had been heated above the δ -transformation point appeared to possess indications of a structure that was not found if this temperature was not exceeded, but the complexity of the markings made any definite conclusions impossible. Pure iron appeared unlikely to give conclusive evidence, and an alloy

containing 1 per cent. of nickel was tried, with more promising results. Etching in a vacuum was discarded, on account of the difficulty of obtaining a tube that was completely impervious to gas at the high temperatures, and finally narrow tubes of silica, containing an atmosphere of pure nitrogen, were used. A polished specimen of alloy was placed in each of two tubes, which were filled with nitrogen at a pressure of 20 mm., sealed, and inserted in a furnace at a temperature of $1300^{\circ}\text{C}.$: they were maintained at that temperature, which was in the γ range, for two hours, at the end of which one was removed and cooled quickly. The other was raised rapidly to $1450^{\circ}\text{C}.$ (within the δ range) in fourteen minutes and similarly cooled. The specimens were removed from their tubes and examined, when a striking difference between the two was found. The appearance of the specimen heated for two hours at $1300^{\circ}\text{C}.$ is shown in micro. No. 1, at a magnification of 50 diameters. It indicates a system of polygonal crystals, which may be assumed to represent the γ -iron that existed at the annealing temperature. The appearance of the other sample that had been similarly heated to $1300^{\circ}\text{C}.$ for two hours, but had finally been raised to $1450^{\circ}\text{C}.$ in fourteen minutes before cooling, is shown in micro. No. 2 (Plate XIV.), also at a magnification of 50 diameters. A system of well-defined crystals, of larger size than those shown in No. 1, is indicated, together with a confused mass of markings, on a smaller scale, that appear to represent previous systems of crystals. While it is thought that the well-defined large crystals represent the structure of the δ -phase that existed when the alloy was removed from the furnace, and the ill-defined smaller crystals the γ -phase that existed previously to the formation of δ -iron, this is not conclusively proved by these observations, since it may be argued that the large crystals of No. 2 are γ -iron crystals that have grown larger as a result of heating to a higher temperature. Examination under a higher magnification, however, indicates other differences. In the sample heated for two hours at $1300^{\circ}\text{C}.$ the "crystals" are found to be crossed by a system of markings, probably formed as a result of the volume change at A3 on cooling. It was observed that these markings were approximately parallel in any one crystal, but that they did not cross a crystal boundary, as is shown in micro. No. 3 (Plate XV.), at a magnification of 150

diameters. In the other sample similar markings were found, but they appeared, as a rule, to be unrelated to the boundaries of the coarse "crystals," or to those of the smaller but less distinct crystals already mentioned. These features are shown in No. 4. The well-defined black boundaries represent the crystals that

IRON-NICKEL ALLOYS

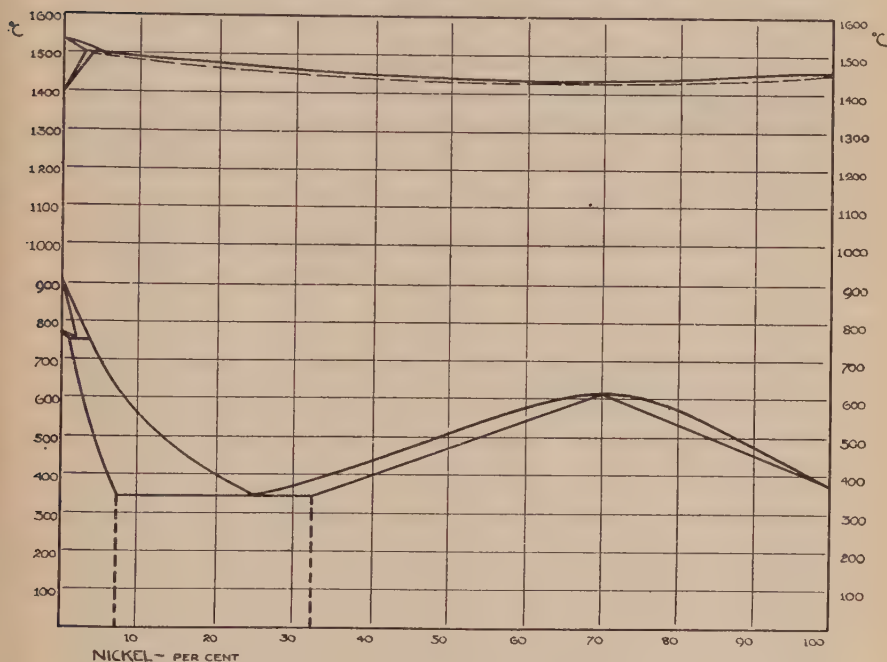


FIG. 6.

existed when the specimen was removed from the furnace, while the less distinct, shadowy "boundaries" mentioned above are also visible (they are best seen if the photograph is held some distance from the eye). The surface markings, which suggest wrinkles, are clearly visible, and they appear to be quite unrelated to these systems of boundaries. The presence of markings of this kind, not related to the coarse crystal grains, is explained by assuming that these crystals were δ -iron, which have changed into a completely new system of γ -iron crystals during cooling,

and that the markings are due to the $\gamma \rightarrow \alpha$ change, in which the newly formed crystals of γ -iron only could take part. These observations indicate a change in the crystal structure at the $\delta \rightarrow \gamma$ transformation temperature. They confirm Dr. A. Westgren's conclusion,¹ based on X-ray analysis, that δ -iron and γ -iron are constitutionally different.

COMPLETE CONSTITUTIONAL DIAGRAM OF NICKEL-IRON ALLOYS.

If the results obtained in this paper be combined with those given in the paper by D. Hanson and H. E. Hanson, in which the constitution of the alloys at lower temperatures is described, it is possible to construct the complete equilibrium diagram for the iron-nickel system. This is given in Fig. 6.

¹ Westgren, *Journal of the Iron and Steel Institute*, 1922, No. I. p. 241.

DISCUSSION.

Dr. W. ROSENHAIN, F.R.S. (Teddington), said the paper represented a piece of work which had been carried out at the laboratory which he himself had the pleasure of supervising, and there was naturally not very much he could contribute to the discussion, except to draw attention to one or two points. The research was interesting owing to the fact that it was, he believed, the first occasion on which they had had at the Metallurgy Department of the National Physical Laboratory a collaborator who was actually a member of the staff of the United States Bureau of Standards—an institution which they regarded, in a sense, as their “opposite number” in America, and with which they maintained very friendly relations, which, he hoped, would develop into an occasional interchange of staff, to the mutual benefit of both institutions.

The work itself had been undertaken some little time ago in anticipation of a much wider programme, of which it really formed the beginning. The National Physical Laboratory was contemplating the undertaking of the systematic study of the alloys of iron with other elements, in the first place, free from carbon. The effect of carbon on those alloys was really extraordinarily great—so great that one could hardly anticipate the magnitude of the effects which a small amount of carbon produced in many cases. Incidentally, that raised the very great difficulty of keeping carbon out of such alloys—a difficulty which the authors had overcome in the present case, and a difficulty which had been overcome, after considerable effort, in certain other cases. The importance of it was that if it were known what the alloys were—what their constitution really was—and whether they were entirely free from carbon, a definite basis would be afforded on which could be erected a knowledge of the more industrially important alloys which did contain carbon. Unless what the entirely carbon-free material really did were known, that knowledge could never be complete and sound. From that point of view, if a paper such as that which the authors presented needed any defence at all from a charge of being entirely academic, he thought the defence lay there.

There were two interesting points in the equilibrium diagram to which he would like to call the members' attention. The case involved was that of a solid solution system. The authors had found a series of solid solutions with a minimum in the liquidus and a maximum in a low temperature transformation in the solid alloys.

He thought the explanation of that had now been given, mainly by the work of some American investigators working on the internal

structure of those crystals by means of X-ray analysis. Those investigators found that the solid solution of iron and nickel might either be a solution of iron in the nickel lattice—the nickel lattice being a face-centered cube lattice—or of nickel in alpha-iron or in gamma-iron as the case might be. In the solidification of the liquid alloys near the iron end of the system, of course, gamma-iron would be formed, and this also had a face-centered cubic lattice, but of distinctly different dimensions. Apparently what happened was that when iron atoms were put in the nickel lattice, that lattice was expanded slightly, with a consequently depressed freezing point. When nickel atoms were put into the iron lattice, the same thing happened, and the minimum was reached at a point where that depression of freezing point, due to the lattice expansion, was the same, and where the dimensions of the two lattices had also become the same. Exactly the same state of affairs was met with in the alloys of manganese and copper.

The lower temperature transformations were in many cases associated with the change from one of those lattices into the other in a region where they were not quite identical. If the members looked at the diagram of Fig. 6, he thought it would be found that between 70 per cent. and 100 per cent. of nickel the transformation was from the nickel to the iron lattice, and in the other case from the iron to the nickel lattice, passing through the change at a certain definite temperature, which appeared to be associated with the normal gamma to alpha change of the iron lattice itself. There was no suspicion even of the existence of a compound at the maximum of the solid transformation. In fact X-ray analysis had definitely proved that there was no compound at that point. There was, however, one very striking fact—a fact which was a little disappointing, because one might have hoped it would have been anticipated from the diagram.

A very remarkable alloy had been discovered in the series. It was a carbon-free iron-nickel alloy. It had been discovered in the laboratory of the Western Electric Company in America. It had been patented and was being exploited commercially. It was an alloy containing $81\frac{1}{2}$ per cent. of nickel and $18\frac{1}{2}$ per cent. of iron. It lay, therefore, decidedly to the right of the maximum in the diagram under discussion, and was not at first sight associated with that maximum at all; but the alloy had a very definite composition, and if an appreciable departure were made from that composition, the particular remarkable qualities of that alloy were lost. Those properties were mainly interesting from the magnetic point of view. The material had the property of becoming magnetically saturated under a very low magnetising force—so low that it required a magnetising force not much greater than the earth's field to saturate it completely. That meant for those low magnetising forces that its permeability was enormously greater than that of pure electrolytic iron. If that alloy were subjected to any kind of treatment—mechanical stress, for

instance—if a wire or a strip of it were put under magnetic test, and pulled with the fingers, the stress exerted was sufficient completely to throw the magnetic instrument off the scale. If it were strained or pulled in a machine so as to alter its length, it became something in the order of one thousand times less permeable under low inductions than it was in the original state. It was a material of very remarkable magnetic properties which were highly unstable. They could be very easily upset. What it depended upon might be just that balance of the two lattices—the nickel and the iron lattice—and when that balance was at that particular point, an enormous magnetic sensitivity was obtained, but the moment that arrangement was upset by strain, or by alteration of composition, or anything else, that magnetic sensitiveness vanished. The magnetic property was admittedly atomic, but was much affected by any distortion of the atom, and therefore by any disturbance of a lattice.

That alloy was likely to be of practical importance because it could be wound on a copper conductor as an inductance loading for telegraph and telephone cables, and it was likely to prove of considerable value by increasing the rate of transmission over such cables and enhancing the clearness of telephonic conversation. An interesting point was that when it was wound round a copper cable, the mere winding strained the alloy sufficiently to spoil it magnetically, and the whole conductor—the copper with the alloy wound upon it—had to be annealed afterwards in order to re-soften the alloy. It was a remarkable instance of an alloy of a group, apparently only of purely scientific interest, proving likely to be of practical value. It emphasised the point which he had been trying to make for some time, that a research on fundamental alloys of iron and other metals was certain to lead to extraordinarily valuable results, but it was not possible foretell what precise direction they might take.

The study of that equilibrium diagram, which was now possibly fairly complete—(he hesitated to call any equilibrium diagram quite complete, because somebody with a little more patience was always discovering something which had been left out)—was a step in the direction which it was hoped to pursue more fully, as time and means permitted, with other alloys of iron.

Dr. W. H. HATFIELD (Sheffield) said the authors' paper was one of those exceedingly valuable contributions which were so much needed at the present time. He hoped the authors would extend the work as quickly as possible to the other binary systems, and also to a few ternary systems. He would suggest that the authors dealt with the iron-nickel carbon series. If they did so, that would bring those alloys into the industrial range immediately.

Colonel N. T. BELAIEW, C.B. (London), said the authors, and the National Physical Laboratory, had to be congratulated on an extremely

interesting piece of work. The diagram of the iron-nickel alloys was extremely important and very interesting; and no doubt it had been very difficult to bring it to the conclusion to which the authors had brought it. The importance of the diagram lay in the fact that the celestial meteorites were iron and nickel alloys. The authors had now rendered available a complete diagram of iron and nickel alloys, and a certain comparison could be made of the structures which were to be anticipated in the meteorites. With regard to the very important spot on the curve between the delta and the gamma modifications, and in respect of the structure of meteorites, in the usual diagram of the iron carbon alloys there were certain practical and theoretical difficulties in understanding some of the structures which investigators were always having as Widmannstätten figures. In order to explain some of the structures which were obtained in the iron carbon alloys during the granulation period, it had to be admitted that, first of all, there was the dendritic process, and then afterwards there was a change of phase between the dendritic structure and the secondary crystallisation in the range of temperature somewhere between 1300° and 700° . Several years ago, when he had met with that difficulty of explaining the occurrence of that new granular structure, he had been bound to assume that there must be a certain change of phase between those two lines. The explanation had appeared when the results had been published of the delta phase, and it had become quite clear that there was in the solid solutions region a certain change of phase. When it had been made clear that there was a certain change from delta to gamma, the structure which appeared in the Widmannstätten structure—the granular structure combined with Widmannstätten figures—became quite clear. But the point arose that exactly the same structure was being obtained not only in iron carbon alloys but also in iron-nickel alloys; and he had to confess that, up to the time of reading the authors' paper, he had been at a certain loss even to take advantage of the occurrence of the delta phase in the iron alloys, because the Widmannstätten figures in the meteorites still remained to a certain extent a puzzle. Now that he realised that up to the amount of 4 per cent. the delta phase had been proved, and brilliantly proved, by the authors, he would like to draw attention to the fact that that small curve in that other portion of the equilibrium diagram meant, from the scientific point of view, an extremely important thing. It meant that the puzzling question which related to the formation of the Widmannstätten figures, not only in iron carbon alloys but in iron-nickel alloys, had been solved by the authors at the National Physical Laboratory.

Dr. F. C. THOMPSON (Manchester) said the work of Dr. Hanson and his co-worker was so good as to place it above criticism of any kind. It was a piece of work which one was glad had been done in an English laboratory. The earlier work by Dr. Hanson and Mrs. Hanson had been an extremely fascinating addition to the knowledge of the subject,

and now that the solidus and liquidus had been added to the diagram, investigators now had, he believed for the first time, a complete diagram of one of the iron alloys. Dr. Hanson had suggested—certainly not insisting on the point—that there was a relationship between the minimum in the liquidus and the maximum in the solidus. Personally he thought it was at least probable that there was no relationship whatever, but simply a coincidence. He did feel, however, that the evidence for a compound in the solid state was at any rate sufficiently great not to put it out of court altogether. Dr. Rosenhain had suggested that the fact that the X-ray method had failed to show any evidence of that compound conclusively proved that it did not exist. That, however, was far from being the case. X-ray examination had never been a suitable method for determining whether compounds were present or not. The question, therefore, at the present time was not affected by the X-ray examination at all. The compound might still be there, although no evidence had been found of it from the X-ray analysis; in fact that was one of the weaknesses at the present time of X-ray examination—that it failed to detect a compound and to differentiate it from a solid solution.

The other point to which reference might be made was the question—which Dr. Rosenhain had also raised—in connection with the space lattice, of the remarkable alloy to which Dr. Rosenhain had referred. Personally he had not heard of that alloy before, and it was a very remarkable material. There did not appear, however, to be any very definite relationship between the space lattice and the magnetic properties. At first sight one was inclined to believe that an open-packed iron was magnetic and a close-packed iron was non-magnetic, and, therefore, to assume that the magnetic properties were due to the packing of the crystals. As Hull, however, had pointed out, chromium and α -iron had the same crystal structure, yet one was non-magnetic and the other magnetic. Nickel and γ -iron were both close-packed cubic crystals, yet the first was magnetic and the latter non-magnetic. The evidence, therefore, at the present time, was that the space lattice had nothing whatever to do with the magnetic properties. Quite recently, while examining some models of open-packed and close-packed crystals, he thought he had obtained evidence to the effect that there was a possibility of obtaining by cold work a change over from open-packed to close-packed iron, and if that did turn out to be correct—it was too early to dogmatise on that point—one would have the interesting example that at room temperatures one had close-packed iron which was distinctly magnetic.

¶ In conclusion he again desired to congratulate the authors on what he considered was one of the most valuable pieces of work which, at any rate, had ever been done in that direction.

CORRESPONDENCE.

Professor E. D. CAMPBELL (Ann Arbor, Michigan) wrote that the care with which the materials were selected and the pains taken to insure accuracy in the determination of the freezing points of the different alloys left no doubt concerning the reliability of the experimental data given in Table I. and shown graphically in Fig. 2. A question might be raised whether the experimental data pointed convincingly to the existence of a definite metallic compound, FeNi_2 , or whether the experimental facts might not be explained by the progressive atomic substitutions of Ni atoms for those of iron in an eight-atom crystal unit. It was difficult to conceive of a cubic space lattice which did not involve at least eight atoms.

It had been noticed by metallurgists for a good many years that if one-eighth of the iron atoms in pure iron were replaced by an isomorphous metal such as Mn, Cr, or Ni, giving an empirical formula Fe_7M alloys, solid solutions, or mixed crystals, as denominated by different authors, were produced, differing very profoundly in properties from those of the constituent metal.

A simple model which had been used in his (Professor Campbell's) laboratory for a number of years to illustrate how a cubic space lattice arrangement of atoms might be obtained from a crystal unit consisting of eight atoms, or four molecules of a simple compound such as sodium chloride, was shown in the accompanying Fig. A.

If it were assumed that in the figure the cube at the end of a small block represented the sodium atom, while the chlorine was represented by the octagon at the other end, and that the molecules possessed polar force fields, it might be very readily seen how, under the well-known law of attraction and repulsion of force field, the molecules, if free to move as when in solution or in the fused state, would be oriented into cubes from which larger cubes of any size might be built, and that in those larger cubes the space lattice relations of the sodium and chlorine atoms were all that were required for a cubic crystal lattice.

It was entirely conceivable how crystal units of eight atoms each might be formed in liquid metallic solutions in a manner perfectly analogous to that leading to the formation of cubic crystals of NaCl , or other salts, from liquid solutions or the fused state.

In the author's diagram, as long as less than one-half the crystal units contained any Ni atoms replacing iron—that was, not more than one atom of Ni to about sixteen atoms of iron—the character of delta iron would predominate, but when the concentration of Ni atoms increased, the gamma iron state alone was manifested and the freezing

point continued to be lower with increasing substitutions of Ni for iron atoms in the crystal unit. That would continue until a eutectic mixture, $2\text{Fe}_3\text{Ni}_5$ (63.6 per cent. Ni) with Fe_2Ni_8 (75.9 per cent. Ni), equivalent to 8FeNi_2 (67.7 per cent. Ni), was reached. With further substitutions of Ni the properties and freezing point would gradually approach those of pure nickel.



FIG. A.

Dr. HANSON wrote, in reply to the correspondence, that he wished to thank Professor Campbell for his interesting communication. The authors did not think that the existence of the compound FeNi_2 was definitely established; their experiments were inconclusive on that point. Professor Campbell's explanation of the crystal structure of such solid solutions was interesting; if it were assumed that the distribution of the atoms was as uniform as possible, then any unit cube could be expressed by $\text{Fe}_n\text{Ni}_{8-n}$, where n is not greater than 8, and any alloy by a mixture of two kinds of such unit cubes. The reason for the minimum on the liquidus and the maximum on the low-temperature transformation curve did not, however, appear to be clearly indicated; to describe the alloy as a eutectic of $2\text{Fe}_3\text{Ni}_5$ and Fe_2Ni_8 was, perhaps, a little misleading, although, in its widest sense, it was but another way of stating the fact.

Iron and Steel Institute.

A CONTRIBUTION TO THE STUDY OF
HARDNESS.

BY PROFESSOR C. A. EDWARDS, D.Sc., AND CHARLES R. AUSTIN,
M.Sc.TECH., A.I.C. (BOTH OF UNIVERSITY COLLEGE, SWANSEA).

A CONSIDERABLE number of investigations have been devoted to the study of making hardness determinations of metals, so that the literature on the subject is very extensive. In view of this, references will in the present instance only be given to those publications which appear to have a definite bearing on the particular aspects of the problem which are dealt with in the present paper. An excellent bibliography of papers published up to 1916 is given in the *Journal of the Institute of Mechanical Engineers*.¹

In his papers before the Paris Congress on Testing Materials in 1895 and 1900 Martel² communicated the results of his researches on dynamic indentation tests. Using quadrangular pyramids of varying shapes and sizes dropped from heights of 100 millimetres to 1000 millimetres, Martel arrived at the following conclusions:

1. Under the same conditions the volume of indent is proportional to the height of fall.

2. The volume of the indentation is proportional to the weight of the hammer and is independent of the shape of the striker.

3. The ratio, energy of impact to the volume of the impression, is constant for any given metal, and independent of the elements of the test.

It was this constant which Martel suggested should be used as the hardness number. Some interesting additional evidence

¹ "Report of the Hardness Tests Research Committee," *Proceedings of the Institute of Mechanical Engineers*, November 1916.

² "Commission des Méthodes d'Essais des Matériaux de Construction," tome iii., Section A (Métaux), 1895, pp. 261-277.

on this kind of test is given in papers by Batson,¹ Unwin,² Edwards and Willis,³ and Edwards.⁴

In the last-named paper it was shown that, "As regards lead, the energy required to displace unit volume of metal, when using cones whose angles varied from 28° to 90°, was the same in each case; this agrees with Martel's law. . . . This cannot be said to apply with certainty to aluminium and tin, but it is quite possible that the observed differences in this connection may be due to the manner in which the measurements were made. The results obtained for lead with the four cones, and the 5, 7, and 10 milli-

metre hemispheres, show that $\frac{E}{\bar{V}}$ is constant for each type of striker; but there is a substantial difference in this respect when the values for the two types are compared with one another.

It is somewhat remarkable that whilst $\frac{E}{\bar{V}}$ is constant for the 5, 7, and 10 millimetre hemispheres, it varies very considerably with varying impacts with the 15-millimetre hemisphere."

From the foregoing observations it is evident that the ratio $\frac{E}{\bar{V}}$ is not entirely independent of the shape of the striker. In view of the peculiar and irregular form of the striking point of the hammer used in the well-known Shore scleroscope, the above is perhaps not without significance when comparisons of scleroscope and Brinell values are made. Another and perhaps more important reason for the lack of perfect agreement between these two methods is that in the former a constant height of fall is used, and therefore the degree of deformation produced differs for materials of varying hardness. This, of course, must be reflected in the proportion of energy that is used to that which is measured in the form of rebound, but no correction is made for this variable factor. It was mainly with a view of throwing more light on this aspect of the problem that the present investigation was undertaken.

The work may be conveniently grouped as follows :

¹ Batson, *Journal of the Institute of Mechanical Engineers*, 1918.

² Unwin, *ibid.*

³ Edwards and Willis, *ibid.*

⁴ Edwards, *Journal of the Institute of Metals*, No. 2, 1918.

A determination of the relationship existing between :

1. Heights of fall and heights of rebound.
2. Heights of fall and volumes of indents produced.
3. The Brinell hardness numbers and the rebounds obtained from falls that gave a certain constant volume of indent.
4. The Brinell hardness numbers and rebounds obtained from a constant height of fall.

Each of these sections will be considered separately and then collectively discussed in a later section.

APPARATUS.

A convenient piece of apparatus for the work in hand was obtained by a modification of the Shore scleroscope.

The frame holding the glass tube, scale, release, and suction arrangement was unscrewed from the vertical ratchet and simply replaced by a frame capable of holding strong glass tubing of sufficient internal diameter to allow a 10-millimetre steel ball perfect freedom to drop down on to the specimen, clamped down on the base of the apparatus in the usual way.

The tubing freely slid into place and could be replaced by similar glass of various known lengths, levelling being effected in the ordinary manner so as to ensure the tubes being perfectly vertical. A vertical paper scale was prepared to fit at the back of the glass tube, the units of measurement used being centimetres shown in bold figures, these again being subdivided into millimetres. With the aid of a lens it was found possible to obtain the various heights of rebound correct to half a millimetre.

Various specimens (where possible about 2 inches square and half an inch in thickness) were prepared by first annealing at the appropriate temperature to obtain uniformity of material and removal of stresses ; other specimens were, however, used in the hardened state. The surfaces of all specimens were polished to the same degree corresponding with the 0 emery-paper.

The release of the ball was effected by the use of a small electro-magnet—a wire-wound annealed nail, ground and polished to a fine point, served quite well—when an E.M.F. of about 2 volts was passed through the helix. The whole apparatus was placed on a heavy slab of iron, so that a solid and rigid foundation was obtained.

RELATIONSHIP BETWEEN HEIGHT OF FALL AND HEIGHT
OF REBOUND.

The experimental difficulties that were encountered were greater than at first anticipated, and for two reasons :

- (a) A clear drop on the surface of the specimen was essential, so that the ball on striking the surface did so with the maximum energy derived from any particular height of fall.
- (b) A clear rebound was also an essential feature of each fall-rebound observation that was accepted.

To obtain these two conditions independently was not difficult, but to obtain them conjointly required repeated attempts when the height of fall reached about 70 centimetres or more. This difficulty was, in part at least, due to the inability to obtain perfectly straight glass tubing of uniform bore when a length of 50 centimetres and upwards was required.

With each of the specimens of metal prepared, observations of height of rebound were recorded for heights of fall varying from 20 centimetres to 100 centimetres by equal increments of 10 centimetres.

Many observations from each particular height of fall were noted, and the mean values of the data obtained for each experiment, where a true fall and rebound were judged to have been effected, were accepted.

With the softer metals, such as copper, aluminium, and brass, the adoption of the plan just mentioned resulted in maximum rebounds being chosen as accepted data, because so many closely agreeing rebounds were obtained for each of the heights of fall.

On the other hand, with some of the harder specimens exceptionally high values were occasionally obtained which could not possibly be taken as being typical of the material for the corresponding height of fall. These abnormal values were only revealed in those materials which were not absolutely homogeneous, and the authors believe they were due to the ball having fallen upon exceptionally hard spots or constituents in the alloy. In such instances a large number of other values in close agree-

ment afforded data which were regarded as being really typical of the substance in question.

At this stage it may be useful to note that in experiments that were conducted towards the end of the investigation rebound observations were made with certain of the specimens, from falls of 100 centimetres and more, without the glass tube. It was found that the error due to friction, &c., between the ball and the walls of the tube was very small for the softer metals.

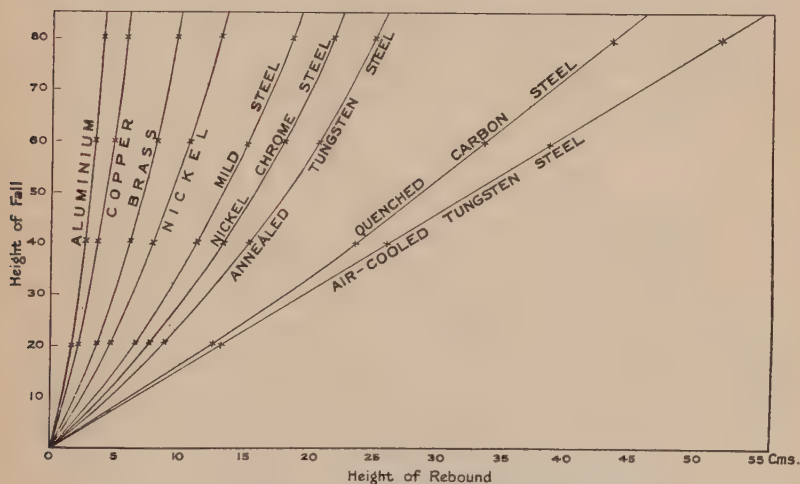


FIG. 1.—Relation between Height of Fall and Rebound.

This is as would be anticipated, for with any given height of fall (say 70 centimetres) the error, due to friction, in the rebound figure when using the glass tube will largely depend upon the height of rebound, or, in other words, on the hardness of the metal under examination. Thus for the soft metals very little difference was observed between the rebound readings taken with and without the tube even from heights of fall up to 100 centimetres. As just intimated, a few observations were made without the use of the glass tube. This was only necessary for falls of less than 100 centimetres when experimenting with the samples of hard carbon and hard tungsten steel.

The results are tabulated for each specimen in Tables I. to XII. When these data are plotted as in Fig. 1 it is clearly seen

that the relationship between the height of fall and the height of rebound is represented by a curve, which indicates that the height of rebound is not proportional to the height of fall. It is evident that all the curves are of the same type and show a decided deviation from a straight line, with the exception of that which represents the fall-rebound ratio for the air-hardened tungsten steel. In this instance it would appear that, within the limits of experimental error, we have a case where a simple

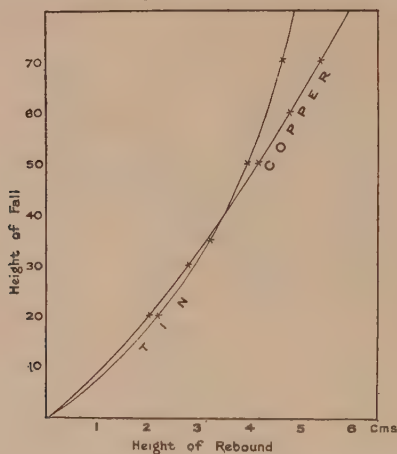


FIG. 2.—Fall-Rebound Curves of Copper and Tin.

linear relation between height of fall and rebound exists, and it is of particular interest to note that this proportionality persists even to the height of fall of 150 centimetres. In the case of cupro-nickel the curve is practically coincident with that for mild steel. The deviation from the straight line relationship is more marked in the case of tin than in any other metal tested. This is shown in Fig. 2, where the data for tin and copper are plotted in the same diagram.

RELATIONSHIP BETWEEN HEIGHT OF FALL AND VOLUME OF INDENT PRODUCED.

Fresh specimens of some of the same metals were polished and indents made by dropping a 10-millimetre steel ball from different fixed heights. As these experiments were undertaken

merely for the purpose of measuring the indentations the glass tube was discarded. In this way distortion of the indentation was avoided because the ball rarely fell in the same place after the rebound. The volume of the indent was calculated from measurements of the diameter of the indent; this measurement was in all cases made by means of the Reichert micrographic apparatus.

The outer edges of the indentations were focused on the ground glass plate on which was printed a scale, and the number of divisions noted over which the diameter of the image extended. From these observations the actual diameters were calculated in the usual way, and their volumes by use of the formulæ,

$$h = d - \sqrt{d^2 - r^2}$$

$$V = \frac{\pi}{3} h^2 \left(\frac{3}{2} d - h \right)$$

where h = depth of indent, d = diameter of indenting sphere, r = radius of indent, and V = volume of indent.

The volume of indents are recorded in Tables I. to XII. In the case of the harder metals it was found impossible to measure the indents produced by drops from 20 centimetres, 40 centimetres, and 60 centimetres, because of the difficulty of focusing the edge of the indent, owing to there being an insufficiently clear line of demarcation between the impression and the normal surface of the specimen; hence in these instances drops of 150 centimetres were used and the diameters of the indents measured with great care.

With each specimen that was examined the various volumes of the indents produced have been plotted against the corresponding energy that was absorbed in producing them. This energy was taken as being represented by the difference between the height of fall and the height of rebound. The curves are shown in Figs. 3 and 4, from which it will be seen that the amount of deformation expressed in terms of the volume of indent is a linear function of the energy absorbed.

At this stage it may be useful to draw attention to another investigation on hardness testing by means of a loaded drop-ball method,¹ which was published after the completion of the greater part of the work embodied in the present paper. Wüst and

¹ Wüst and Bardenheuer, "Hardness Testing by the Loaded Drop Ball Method," *Mitteilungen a. d. Kaiser-Wilhelm Institut für Eisenforschung*, 1920, vol. i. pp. 1-30.

Bardenheuer drew two main conclusions as a result of their observations, which were as follows :

- (1) The ratio of the energy expended to the fourth power of the diameter of the indent is a constant quantity.
- (2) The ratio of the energy expended to the volume of the indentation is a constant quantity.

The first of these conclusions is identical with the one arrived

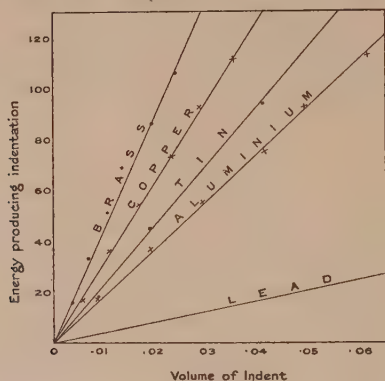


FIG. 3.—Relation between Net Energy and Amount of Deformation.

at by Edwards and Willis in 1918, whilst the results depicted in Figs. 3 and 4 are in accord with the second.

It is probable that the second conclusion, though true in general, requires some qualification, and that the linear ratio is not absolutely constant when the diameters of the indents are measured and not the depth. Under the former conditions the

apparent $\frac{E}{V}$ might vary when the values of E are widely different.

In other words, errors in the calculated figures of V from the measured diameters are no doubt more serious when large indentations are produced, owing to the more marked piling up of material round the sides of the indent. With very small indentations, such as have been produced in the present investigation, this particular defect is negligible.

The small amount of deformation caused by the low values of E did not allow of a careful analysis of the condition holding between volume of indentation and energy of impact for the

hardest metals. There is, however, little doubt that these fall in line within the ranges here considered.

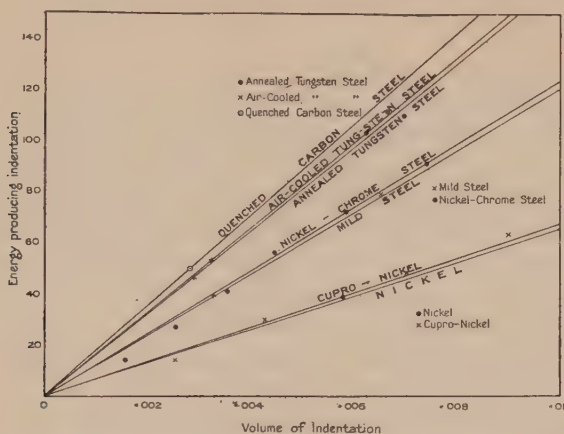


FIG. 4.—Relation between Net Energy and Amount of Deformation.

RELATIONSHIP BETWEEN THE BRINELL HARDNESS NUMBERS AND THE RESPECTIVE HEIGHTS OF REBOUND WHEN SOME STANDARD VOLUME OF INDENT IS PRODUCED.

The data obtained by means of the falling ball test have been examined and an attempt made to correlate these with the Brinell hardness values. An examination of the fall-rebound curves (Fig. 1), in conjunction with those for energy-volume (Figs. 3 and 4), shows that an indent of constant volume of about 0.0083 cubic millimetre is perhaps the most convenient to make use of. Greater volumes require too great a fall to produce them, when dealing with the hard metals, to permit of a reasonably accurate rebound observation being taken. Smaller volumes require so small a fall for the soft metals as again to render the rebound observations less reliable. Hence in the case of each specimen that was examined, the particular height of fall required to produce a standard indent having a volume of 0.0083 cubic millimetre was determined by means of the curves, whilst the corresponding rebounds were obtained in a similar manner from Fig. 1.

For convenience, the data are given in Table XIII., and they are also plotted against the corresponding Brinell hardness

values in Figs. 5 and 6. In the former all the results are included in the diagram, whilst in the latter only those for the softer metals are given, the object being to use a much more open scale.

On examining Fig. 5 it will be noted that, with the exception of tin, iron, and the cupro-nickel alloy, the relationship between the rebounds, obtained after allowing the ball to fall from heights which would give the standard indentation, and Brinell values is represented by a very fair curve; the higher portion, that is, corresponding with Brinell hardnesses above 250, being apparently a straight line. The exceptions which have been mentioned each gave a higher rebound than would be expected from a consideration purely of their Brinell values. It is interesting to note the equation which expresses the lower portion of the curve, that is, up to a value of 250 Brinell.

Retaining the units which have been used throughout the paper, rebound in centimetres and Brinell numbers as usually calculated, if H = Brinell hardness number and R = rebound in centimetres, it is found that

$$H = 57\sqrt{R}, \text{ i.e. } H = a\sqrt{R}.$$

In other words, the Brinell numbers for this range of metals vary as the square root of the rebound obtained when a constant amount of deformation is produced.

RELATIONSHIP BETWEEN THE BRINELL HARDNESS NUMBERS AND THE RESPECTIVE HEIGHTS OF REBOUND OBTAINED WITH A STANDARD HEIGHT OF FALL.

For this particular purpose we may use the results which have already been considered in other connections. The necessary figures for falls of 25, 50, and 75 centimetres are illustrated in Fig. 7 (p. 334), where they are plotted against the Brinell values of the corresponding materials. The observed values from which the curve depicting the results from a height of fall of 50 centimetres have not been plotted in the diagram, simply because their inclusion would tend to make it less easy to see how the various points lie in regard to the respective curves which have been drawn. From the lowest curve in this series it will be

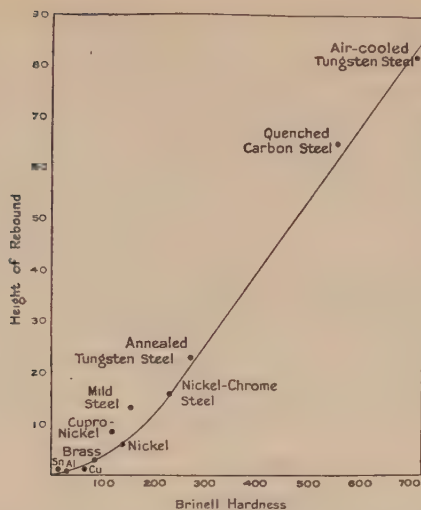


FIG. 5.—Relation between Rebound, after a Standard Indentation, and Brinell Hardness.

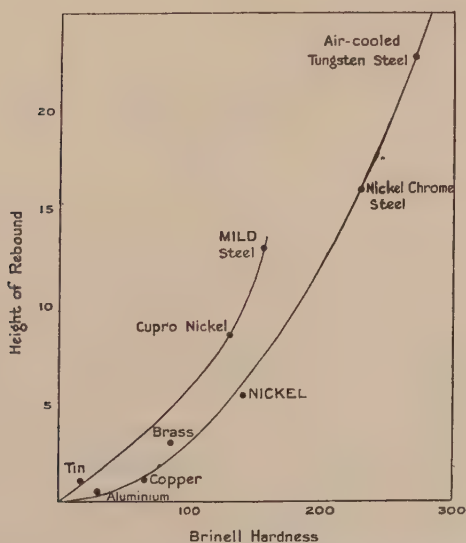


FIG. 6.—Relation between Rebound, after a Standard Indentation, and Brinell Hardness.

quite readily seen that the rebounds obtained after dropping the ball from a height of 25 centimetres are very much the same, when the Brinell value is greater than about 300. Under these conditions, therefore, the dynamic method fails to discriminate between metals which are more than moderately hard. This

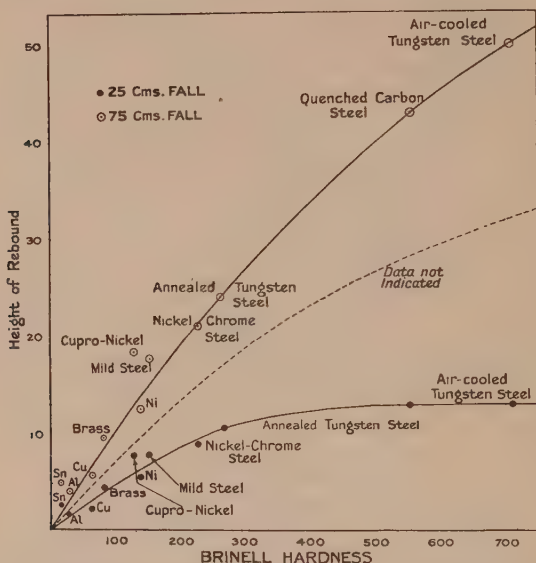


FIG. 7.—Relation between Rebound, with Constant Heights of Fall, and Brinell Hardness.

fact was, of course, to be anticipated from a consideration of the fall-rebound diagrams in Fig. 1.

This, however, ceases to apply when we consider the results obtained when using greater heights of fall. It will be seen that there is a progressively marked increase in the steepness of the curves as the height of fall increases, and with a fall of 75 centimetres it would seem possible, by the dynamic method, readily to distinguish between metals which, though having high Brinell hardnesses, differ but little in their actual numerical values.

On further consideration it would seem that, by increasing the height of fall to something above 75 centimetres, the relationship under such conditions might be found to approximate more closely to a straight line.

In view of these facts it would certainly seem possible to design an instrument which would give rebound data that could be easily converted into Brinell figures. To do this, however, it would be necessary to keep the following points clearly in mind :

- (1) The medium imparting the requisite energy should be spherical at the part where it makes contact with the specimen under examination.
- (2) The height of fall, or at least the energy at the instant of impact, should be high enough to produce a rebound that would readily discriminate between very hard materials possessing different Brinell values. It would, no doubt, be inconvenient to use very high falls, but this could be overcome by loading the ball.

DISCUSSION OF RESULTS AND CONCLUSIONS.

As previously stated in the earlier part of the present paper, there does not appear to be any simple relationship between the rebound method of measuring hardness and Brinell's static method, and it is therefore not readily possible to express one in terms of the other by the use of a conversion scale. If only small amounts of energy are used in the drop test, there is comparatively very little difference in the height of rebound that is produced after striking metals whose hardness is above a Brinell value of, say, 300. Hence rebound observations under these conditions are worthless for the purpose of discriminating between hard materials.

This limitation, however, becomes less serious as the height of fall is raised, and there appears to be some reason for considering that there might be a linear relationship between the rebound and Brinell values if the height of fall were increased to an extent which has not yet been ascertained. This state of affairs is approximately reached, when using an unloaded 10-millimetre steel ball, if the height of fall is 75 centimetres. There are, of course, many practical objections to using an instrument to give so great a height of fall ; but if, as would appear from previous work, the velocity of impact is not an important factor, then it should be possible to get perfectly satisfactory results by using a loaded ball,

In the Brinell hardness-rebound diagrams the anomalous positions of tin, mild steel, and cupro-nickel may be noted. Each of these substances gave a higher rebound for any given fall than would be expected from their hardness as measured by Brinell's method. This peculiarity has been previously noted for tin and mild steel as well as two other pure metals, namely, zinc and cadmium, and it is thought to be in some way associated with the formation of definite twin lamellæ when these metals are suddenly stressed. The authors have not so far been able to detect this kind of structure in the case of cupro-nickel.

A simple relationship between Brinell values of different metals, and heights of rebound obtained from heights of fall or energy of impact yielding a constant amount of deformation, has been obtained.

TABLE I.—*Aluminium.*

Fall.	Rebound.	Volume of Indentation.
20 cms.	1.6 cms.	0.0091 cub. units
30 "	2.1 "	...
40 "	2.65 "	0.0191 cub. units
50 "	3.05 "	...
60 "	3.45 "	0.0294 cub. units
70 "	3.75 "	...
80 "	4.1 "	0.0419 cub. units
100 "	4.6 " (5 cms.) ¹	0.0491 " "
120 "	...	0.0618 " "

¹ Rebound observed without use of glass tube.

TABLE II.—*Copper.*

Fall.	Rebound.	Volume of Indentation.
20 cms.	2.05 cms.	0.0058 cub. units
30 "	2.8 "	...
40 "	3.55 "	0.0112 cub. units
50 "	4.25 "	...
60 "	4.8 "	0.0172 cub. units
70 "	5.5 "	...
80 "	6.0 "	0.0234 cub. units
100 "	6.55 " (6½ cms.) ¹	0.0286 " "
120 "	...	0.03545 " "
150 "	(10 cms.) ¹	0.042 " "

¹ Obtained without use of glass tube.

TABLE III.—*Brass.*

Fall.	Rebound.	Volume of Indentation.
20 cms.	3.65 cms.	0.0033 cub. units
30 "	4.9 "	...
40 "	6.0 "	0.0069 cub. units
50 "	7.2 "	...
60 "	8.05 "	0.0105 cub. units
70 "	9.25 "	...
80 "	9.85 "	0.0136 cub. units
100 "	11.35 "	0.0196 " "
120 "	...	0.024 " "

TABLE IV.—*Cupro-Nickel.*

Fall.	Rebound.	Volume of Indentation.
20 cms.	6.45 cms.	...
30 "	9.05 "	...
40 "	11.15 "	...
50 "	13.5 "	0.0058 cub. units
60 "	15.4 "	...
70 "	17.5 "	...
80 "	19.5 "	...
100 "	20.7 "	0.0105 cub. units

TABLE V.—*Nickel.*

Fall.	Rebound.	Volume of Indentation.
20 cms.	4.6 cms.	0.00251 cub. units
30 "	6.2 "	...
40 "	8.1 "	0.00447 cub. units
50 "	9.3 "	...
60 "	10.6 "	0.00698 cub. units
70 "	11.9 "	...
80 "	13.3 "	0.00911 cub. units
100 "	14.8 "	0.01257 " "
120 "	...	0.0148 " "

TABLE VI.—*Nickel-Chrome Steel.*

Fall.	Rebound.	Volume of Indentation.
20 cms.	7.1 cms.	0.0013 cub. units
30 "	10.6 "	...
40 "	13.7 "	0.0025 cub. units
50 "	16.0 "	...
60 "	18.0 "	0.00355 cub. units
70 "	20.0 "	...
80 "	22.0 "	0.00446 cub. units
100 "	24.3 "	0.00583 " "
120 "	...	0.00736 " "

TABLE VII.—*Annealed Tungsten Steel.*

Fall.	Rebound.	Volume of Indentation.
20 cms.	8.7 cms.	...
30 "	11.9 "	...
40 "	15.5 "	...
50 "	18.2 "	...
60 "	21.0 "	...
70 "	22.5 "	...
80 "	24.2 "	...
100 "	26.0 "	...
120 "	...	...
150 "	(42.0 cms. ¹)	0.00655 cub. units

¹ Noted without using glass tube.TABLE VIII.—*Air-Cooled Tungsten Steel.*

Fall.	Rebound.	Volume of Indentation.
20 cms.	13 cms.	...
30 "	19 "	...
40 "	26 "	...
50 "	31 "	...
60 "	37 "	...
80 "	52 "	...
120 "	72 "	0.00288 cub. units
150 "	96 "	0.00328 " "

All readings in the table noted without using glass tube.

TABLE IX.—*Mild Steel.*TABLE X.—*Quenched Carbon Steel.*

Fall.	Rebound.	Volume of Indentation.	Rebound.
20 cms.	6.4 cms.	...	12.6 cms.
30 "	9.3 "	...	18.5 "
40 "	11.3 "	...	23.5 "
50 "	13.5 "	0.0032 cub. units	28.0 "
60 "	14.9 "	...	33.2 "
70 "	17.0 "	...	...
80 "	17.6 "	...	45.0 cms.
100 "	21.0 "	0.0065 cub. units	...

TABLE XI.—*Lead.*

Fall.	Volume of Indentation.
50 cms.	0.127 cub. units
100 "	0.225 " "

TABLE XII.—*Tin.*

Fall.	Rebound.	Volume of Indentation.
20 cms.	2.3 cms.	0.009 cub. units
50 "	4.0 "	0.019 " "
98½ "	5.6 "	0.041 " "

TABLE XIII.—*Indicating Heights of Fall required to give a Constant Amount of Deformation and Corresponding Heights of Rebound.*

Metal.	Fall.	Rebound.	Brinell Hardness.
Aluminium	6 cms.	0.6 cms.	30.0
Tin	8 "	1.1 "	17.5
Copper	11 "	1.25 "	65.0
Brass	16½ "	3.1 "	85.0
Cupro-nickel	28½ "	8.7 "	130.0
Nickel	25 "	5.45 "	140.0
Mild steel	47 "	13.0 "	155.0
Nickel-chrome steel .	50 "	16.0 "	230.0
Annealed tungsten steel	68 "	22.8 "	270.0
Quenched carbon steel	120 "	65.0 "	555.0
Air-cooled tungsten steel	131 "	82.0 "	710.0

TABLE XIV.—*Indicating Rebounds obtained for the Respective Metals when Dropping the Ball from Constant Heights of Fall of 25 centimetres, 50 centimetres, and 75 centimetres.*

Metal.	Rebounds obtained from a Fall of :		
	25 Cms.	50 Cms.	75 Cms.
Aluminium	1.9 cms.	3.1 cms.	4.0 cms.
Tin	2.7 "	3.9 "	4.9 "
Copper	2.45 "	4.25 "	5.75 "
Brass	4.3 "	7.2 "	9.5 "
Cupro-nickel	7.9 "	13.5 "	18.5 "
Nickel	5.45 "	9.35 "	12.55 "
Mild steel	7.9 "	13.4 "	17.8 "
Annealed tungsten steel	10.5 "	18.2 "	24.0 "
Nickel-chrome steel	9.0 "	16.0 "	21.0 "
Quenched carbon steel	13.0 "	28.5 "	43.0 "
Air-cooled tungsten steel	13.0 "	32.0 "	50.0 "

DISCUSSION.

Mr. H. O'NEILL (Manchester) said he had been very interested to see a paper by Mr. J. Okubo,¹ entitled "Some Experiments on Impacts." Professor Edwards and Mr. Austin had come to the conclusion that the energy expended in making indentations by the dynamic method varied linearly with the volume of the indentation. Mr. Okubo had come to the same conclusion. He had found that there was a linear relationship between the energy loss of a falling sphere and the volume of indentation which it produced. He had found that the work done to produce an indentation of given size was proportional to the scleroscope hardness number. He (Mr. O'Neill) thought it would have been very interesting if the authors had carried out the scleroscope hardness determinations of their specimens to see how they agreed with the work required to produce a given dynamic indentation. Mr. Okubo had found that the scleroscope hardness number was proportional to that work; and it seemed that one would expect a better relation between the scleroscope numbers than the Brinell numbers.

Dr. L. AITCHISON (Birmingham) said what was urgently required was a system of hardness testing which would not involve the distortion of the metal, and possibly Professor Edwards' work might eventually lead to something useful in that direction.

Mr. A. S. E. ACKERMANN (London) said that he had been at work since 1917 on the physical properties of clay, and Professor C. A. Edwards and Mr. Willis had been at work on metals in a similar manner evidently about the same time, judging by the fact that they published a paper, which was of the greatest interest, but which, unfortunately, he had only recently seen. Since studying Professor Edwards' paper, and a letter on hardness by Mr. Hugh O'Neill and Professor Thompson in *Nature* of December 9, 1922, he (Mr. Ackermann) had found that there were many similarities between the physical properties of clay and of plastic metals. For instance, in the present paper Professor Edwards referred to the work of Martel, in which it was found that the volume of the indentation was proportional to the height of the fall of the loaded ball, or other body causing the indentation. That was true also for clay, both when the indentation was produced by a falling weight, or when it was produced by a steady load. He had found that, using an inverted square pyramid and causing it to penetrate by a steady load, the ratio of the load to the surface of contact between

¹ *Reports of Tokyo University*, vol. xi. No. 6.

the inverted pyramid and the clay was constant for any given percentage of water contained in the clay, but that it was not independent of the angle of the pyramid, that was to say, if two pyramids of different angles were used, then different results would be obtained, but for each particular angle the ratio was constant. On plotting the loads as ordinates, and the penetrations as abscissæ, a series of parabola were obtained closely resembling those obtained by Professor Edwards when testing the hardness of metals. In his case each parabola referred to a metal of a particular hardness, while, in the case of clay, each parabola referred to a particular percentage of water in the clay.

As the result of his work Professor Edwards gave the law of penetration as $d = CE^{0.25}$, where d was the diameter of the indentation in millimetres produced by a 10-millimetre ball, C a constant, and E the energy of impact in pound-inches. In giving that law he mentioned that the value of the index of the power of E was at first found not to be constant, but varied slightly and inversely with the hardness of the metal. Thus in the case of the hardest steel the index was 0.24 and in the case of lead it was 0.27. In the case of clay, he (Mr. Ackermann) had found independently (though the equation was published in an entirely different form) that $d = CE^{0.33}$ where the symbols had the same meaning as before.

It was of interest to note that the value of the index of the power in the case of clay was again a little larger than in the case of lead. It would seem, therefore, that that index was not constant, but increased very slightly as the material tested became softer.

Professor C. A. EDWARDS, in reply, said that in dealing with metals, it was a question of dealing with material the properties of which had in many respects great similarities with those of clay. The only fundamental difference was, that whereas clays appeared to possess a capacity to undergo flow consistently under steadily applied loads, metals apparently developed, as the penetration proceeded, a greater capacity to resist further penetration—what was known as work-hardening effect. In that connection there were many points of great interest to which he would like to refer, but time would not permit him to deal with the matter more than to say that other workers in his laboratory had obtained some extremely interesting results, which would have a bearing on the remarks of Mr. Ackermann and of Mr. O'Neill.

Iron and Steel Institute.

THE VARIATION OF BRINELL HARDNESS
NUMBER WITH TESTING LOAD.

BY HUGH O'NEILL, M.MET. (UNIVERSITY OF MANCHESTER).

INTRODUCTION.

THE great metallurgist Brinell was the first to show⁽⁹⁾ that the hardness number of a steel as determined by his method increased with rise of testing load. This increase he attributed to the greater cold-working of the sample under the higher pressures. In the same communication the effect upon the Brinell number of the application of cold-work to hard and soft steels was reported. The results are quoted here :

TABLE I.—*Effect of 8 per Cent. Reduction of Area (Brinell).*

Carbon.	Manganese.	Condition.	Hardness No.	Increase in Hardness per Cent.
1·2	0·18	As received Cold-drawn	88	...
			89	11·9
0·25	0·40	As received Cold-drawn	45	...
			56·5	25·5

Apart from the mathematical error in calculating the percentage increase of hardness in the first steel, the hardness numbers themselves appear to be wrong. There is no mention that they are not the Brinell numbers obtained in the standard way. But if so, the hardness values for two such unworked steels are given elsewhere by Brinell as being 251 and 143 respectively. These errors do not lend conviction to the following statement : " The conclusion to be drawn appears to be that by cold-drawing the hardness of a soft steel material will be increased to a far greater extent than in the case of a steel of superior hardness." However, this conclusion is confirmed by the experimental work of Goerens.⁽¹⁵⁾

If a soft steel and a hard steel be equally cold-worked, it would appear that the former gives a greater percentage increase of Brinell hardness at any one load than the latter. Suppose also that the rise of hardness number with rise of load is due to cold-working effects, it might then be expected that the percentage increase of Brinell number with increase of testing load on soft steel would be greater than the corresponding increase on hard steel. Tests were therefore made on steels of different hardnesses, and for completeness, further available particulars of these materials are given below.

Ferrous Materials employed.

Steel 2N.—About 0.16 per cent. carbon, 0.14 per cent. manganese; yield point, 17 tons per square inch; maximum stress, 22.6 tons per square inch; reduction of area, 78 per cent.

Steel A.—0.25 per cent. carbon, 0.28 per cent. manganese.

Steel S90.—Swedish Bessemer, about 0.9 per cent. carbon; yield point, 30.8 tons per square inch; maximum stress, 61.5 tons; reduction of area, 16.5 per cent.

Steel W.—About 14 per cent. tungsten, 0.65 per cent. carbon, and 0.25 per cent. manganese, with a little chromium and vanadium. A test-piece of a similar piece of steel with a Brinell number of 305 had an elastic limit of 15.7 tons, yield point 48 tons, and broke suddenly at 52.5 tons, with a reduction of area of 15 per cent.

Steels 4 and 3 were heat-treated pieces from a plain carbon bar containing about 0.9 per cent. carbon.

During the course of these experiments various observations caused the scope of the investigation to be extended, and in particular the work of Meyer⁽¹⁾ became involved.

This well-known research, confirmed by other investigators^(2, 6), has shown that if d be the diameter of the impression obtained with a load L in the Brinell test, then $L = ad^n$, where a and n are constants for a given ball diameter (D) and a given sample of metal.

From Meyer's equation

$$d = \left(\frac{L}{a} \right)^{\frac{1}{n}}.$$

Since the spherical area (A) of an indentation

$$= \frac{\pi D}{2} \left\{ D - \sqrt{D^2 - d^2} \right\},$$

then

$$A = \frac{\pi D}{2} \left\{ D - \sqrt{D^2 - \left(\frac{L}{a} \right)^{\frac{2}{n}}} \right\} = \frac{\pi D}{2} \cdot \frac{\left(\frac{L}{a} \right)^{\frac{2}{n}}}{D + \sqrt{D^2 - \left(\frac{L}{a} \right)^{\frac{2}{n}}}}$$

$$\begin{aligned}
 \text{But the Brinell hardness (H)} &= \frac{L}{A} \\
 &= L \cdot \frac{2}{\pi D} \cdot \frac{D + \sqrt{D^2 - \left(\frac{L}{a}\right)^{\frac{2}{n}}}}{\left(\frac{L}{a}\right)^{\frac{2}{n}}} \\
 &= \frac{2}{\pi D} \cdot \frac{2}{a^{\frac{2}{n}}} \cdot L^{\left(1 - \frac{2}{n}\right)} \left\{ D + \sqrt{D^2 - \left(\frac{L}{a}\right)^{\frac{2}{n}}} \right\}
 \end{aligned}$$

For simplicity this may be written

$$H = yL^x + yL^x \cdot \frac{z}{D}.$$

It follows from this formula that :

- (1) When L is zero the hardness number is also zero.
- (2) As L increases, H also increases, but because of the nature of the second term it passes through a maximum and eventually falls.

Dr. N. Greenwood ⁽³⁾ deduced the following relation between H and L from his investigation of the copper-aluminium alloys :

$$H = K + L^x.$$

If this be correct, then when the load is zero the Brinell number has still a positive value. Such a conclusion is contrary to the relation deduced earlier in this paper.

If reference be made to Greenwood's work, it will be found that he states in the case of the 10 per cent. aluminium alloy, for example, that :

$$H = 10^{1.59} + L^{0.17}.$$

At 3000 kilogrammes load this formula would give a hardness number of 42.8, whereas his experimental result is 152. Now if the equation be read as :

$$H = 10^{1.59} \times L^{0.17},$$

the hardness works out correctly at 152. There is a similar error in all the equations given, and it is apparent that the addition sign should be a multiplication sign. In other words, Greenwood's relation should be :

$$H = KL^x.$$

Considering the Brinell test from the theoretical point of view, the indenting sphere or ball comes into contact with the plane surface of the specimen at a geometrical point. Assume that the

sphere is perfectly rigid and that the specimen is not infinitely resistant; then as soon as the sphere has weight, or is loaded, an infinitely high stress is set up at the point of contact. If the specimen be quite inelastic a permanent impression is always produced. In such a material the load-hardness curve passes through the origin. With a specimen possessing elasticity this infinite stress will cause some elastic deformation, but will most probably produce a permanent indentation. In any case, the load-hardness curve would appear to pass through the origin, or very near to it.

BRINELL NUMBER AT LOW LOADS.

It was decided to investigate the Brinell numbers of steels at very low loads to see if H decreased continuously with L . A 10-millimetre ball was etched for two minutes in 1 per cent. nitric acid and fixed into the dead-loading small Brinell machine made by Messrs. Alfred Herbert, Ltd. The measurement of the diameters of the *shallow* impressions obtained under these conditions with steel was difficult, and was carried out with the small hardness machine microscope. Reading is facilitated if half of the illuminator lens be covered by a piece of metal strip. This strip can be bent at the bottom so as to stand upright on the base plate.

The two steel specimens to be investigated were ground, and finished on 00 emery-paper. *In all the Brinell tests throughout this work at least two impressions were made, two diameter readings were taken of each impression, and the load was always applied for two minutes.*

TABLE II.

Load. Kgs.	Steel A.			Steel W.		
	$d.$	$A.$	$H.$	$d.$	$A.$	$H.$
50	0.848	0.5658	88	0.584	0.2681	186
40 °	0.758	0.4519	89	0.547	0.2352	170
30	0.648	0.3302	91	0.488	0.1872	160
20	0.553	0.2403	83	0.435	0.1486	135
10	0.400	0.1257	80	0.343	0.0922	109
5	0.295	0.06836	73	0.310	0.07548	63
2.45	0.230	0.04157	59	...	...	...

The results are plotted in Fig. 1. In the case of both steels it was very difficult to read the diameters of the impressions at the lowest load, but the results would suggest that H

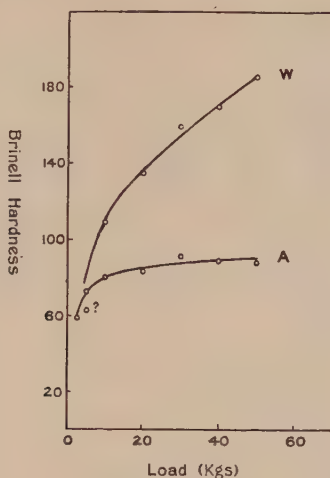


FIG. 1.—10-Millimetre Ball.

decreases continuously with L and that the curve passes through the origin, or very near to it.

BRINELL NUMBER AT ORDINARY LOADS.

It has been shown that the results obtained by Greenwood give the relation

$$H = KL^x$$

for the alloys used by him and the loads generally available. Four steels of increasing hardness have been tested in the same range with the 10-millimetre ball machine, and the results are given in Table III, and plotted in Fig. 2.

If the results be plotted logarithmically the points lie practically on straight lines, and the following values would hold for $H = KL^x$:

Steel A.	$H = 63.L^{0.103}.$
W.	$H = 125.L^{0.120}.$
4.	$H = 164.L^{0.125}.$
3.	$H = 198.L^{0.131}.$

TABLE III.

Load. Kgs.	Steel A.		Steel W.		Steel 4.		Steel 3.	
	d.	H.	d.	H.	d.	H.	d.	H.
3500	5.39	141	3.62	329	...	...	...	...
3000	5.04	140	3.37	327	2.90	444	2.58	564
2000	4.20	138	2.80	318	2.41	432	2.17	534
1000	3.10	129	2.09	288	1.79	394	1.60	495
500	2.30	119	1.53	270	1.35	348	1.20	441

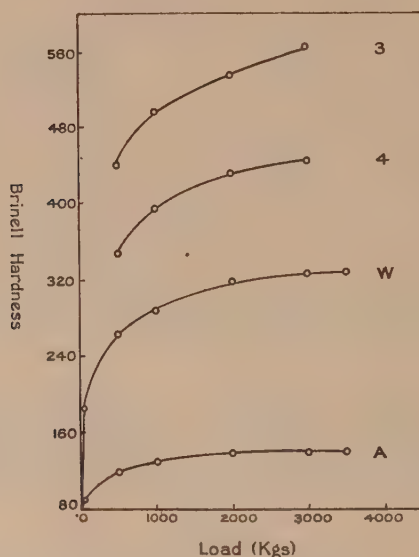


FIG. 2.—10-Millimetre Ball.

With these steels the values of K and α increase with the initial rigidity of the material.

Returning to the point mentioned in the introduction which caused this work to be commenced, Table IV. is of interest: Contrary to expectation, the percentage increase of Brinell number with increase of testing load is lower with soft steel than with hard.

TABLE IV.—*Variation of Brinell Number with Hard and Soft Steels.*

Load. Kgs.	Mild Steel A.		Hard Steel 3.	
	Brinell Number.	Difference per Cent.	Brinell Number.	Difference per Cent.
500	119	...	441	...
3000	140	17·6	564	28·0

BRINELL NUMBER AT HIGH LOADS.

It has been shown that the Brinell number (H) can be represented by

$$H = yL^x + yL^x \cdot \frac{z}{D}$$

where

$$x = 1 - \frac{2}{n}, \quad y = \frac{2a^n}{\pi}, \quad \text{and } z = \sqrt{D^2 - \left(\frac{L}{a}\right)^2}$$

as previously explained.

The nature of the second term indicates that as L increases above a certain value, H will decrease. If values for a and n are obtained, H can be calculated for any load. This has been done for Steel A up to high loads, using the values for a and n obtained experimentally with the 1-millimetre and 10-millimetre balls and reported in Appendix I.

TABLE V.—*Steel A. Calculated Brinell Numbers.*

1-millimetre ball. $a = 150, n = 2.247$.

L.	$\frac{L}{D^2}$.	yL^x .	$yL^x \cdot \frac{z}{D}$.	$\frac{z}{D}$.	H.
10	10	70·6	67·3	0·954	138
30	30	79·7	69·5	0·873	149
50	50	84·3	66·6	0·790	151
75	75	88·1	59·8	0·679	148

TABLE VI.—*Steel A. Calculated Brinell Numbers.*10-millimetre ball. $a = 74, n = 2.288.$

L.	$\frac{L}{D^2}$	yL^x	$yL^x \cdot \frac{z}{D}$	$\frac{z}{D}$	H.
1000	10	65.3	62.0	0.950	127
3000	30	75.0	64.8	0.864	140
5000	50	80.0	62.3	0.778	142
7500	75	84.2	55.4	0.658	140

Results embodied in Table VI. are shown graphically in Fig. 3.

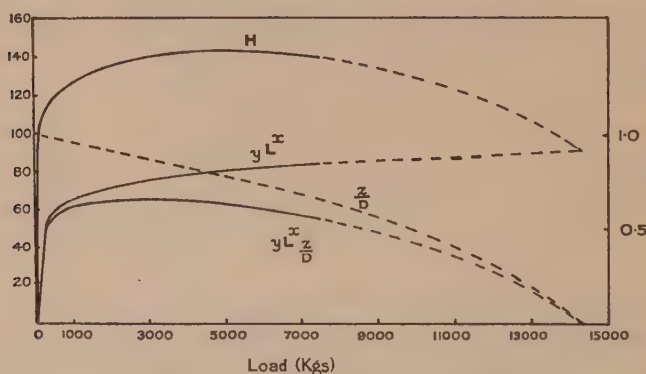


FIG. 3.—Steel A. 10-Millimetre Ball.

If the formula be true it is evident that :

- (1) The Brinell number first increases from zero with rise of testing load, but eventually decreases as the latter passes a critical value.
- (2) This fall in the Brinell number is due to the term $\frac{z}{D}$ decreasing from 1.0 to zero.
- (3) For any given value of $\frac{L}{D^2}$ the value of $\frac{z}{D}$ is approximately the same for balls of different diameters.

Experimental verification of the fall in the Brinell number was obtained by using the small ball hardness machine and

relatively high loads. It has been shown by several workers, notably by Baker, that if the ratio $\frac{L}{D^2}$ be maintained constant when using balls of different diameters, then the hardness numbers are comparable. In Herbert's machine the maximum load is 50 kilogrammes on a 1-millimetre ball, which corresponds to 5000 kilogrammes on a 10-millimetre ball.

TABLE VII.—*Brinell Numbers using 1-millimetre Ball.*

Load. Kgs.	Steel A.		Steel S90.		Steel W.	
	<i>d.</i>	H.	<i>d.</i>	H.	<i>d.</i>	H.
50	0·632	142	0·476	264	0·435	319
40	0·567	144	0·429	263	0·394	315
30	0·489	149	0·374	264	0·339	323
20	0·408	147	0·311	256	0·284	308
10	0·298	140	0·232	233	0·211	283
5	0·221	129	0·172	214	0·156	260

Difficulty was encountered in obtaining constant readings with the highest load and the lowest load on Steel W, but it is apparent that in the mild Steel A the Brinell number falls off as the load of 30 kilogrammes is exceeded. Further experiments on two soft materials gave similar results.

TABLE VIII.—*Brinell Numbers using 1-millimetre Ball.*

L.	Steel 2N.		Armco Iron.	
	<i>d.</i>	H.	<i>d.</i>	H.
50	0·710	108	0·731	100
40	0·641	110	0·665	100
30	0·559	112	0·581	103
20	0·454	117	0·480	104
10	0·330	114	0·350	101
5	0·242	107	0·258	94

Only a small piece of Steel 2N remained for testing with the 10-millimetre ball, and the following figures may not be of a high degree of accuracy.

TABLE IX.—*Steel 2N and 10-millimetre Ball.*

Load.	<i>d.</i>	H.
3000	6.13	91
2000	4.65	111
1000	3.30	114
500	2.38	111

The values of H and L with the 1-millimetre ball are plotted in Fig. 4.

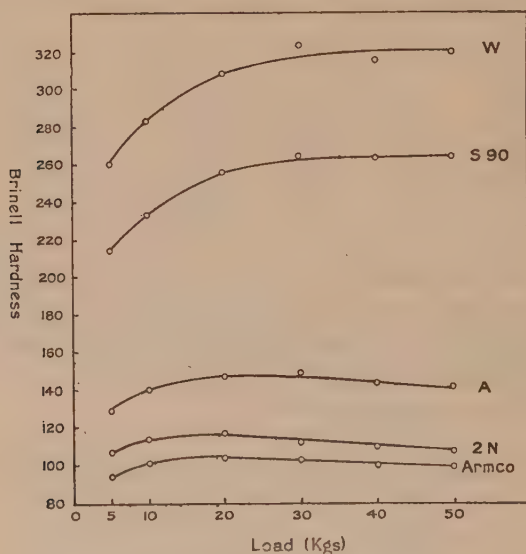


FIG. 4.—1-Millimetre Ball.

This experimental work shows that the original formula is correct in principle. Subsequent examination of the results of previous workers confirms the fall in Brinell number after a certain load has been exceeded.

The hardness figures given by Brinell⁽⁹⁾ for a 0.1 carbon steel (Table III.) show decreasing values. Those obtained by Thomas⁽⁸⁾ for a mild steel are often slightly lower at 5000 kilogrammes than at 3000 kilogrammes load. The Brinell numbers in Table IX. of Greenwood's paper⁽³⁾ are, generally speaking, slightly lower at

4000 kilogrammes than at 3000 kilogrammes. Further examples will be found reported later under the section on Soft Metals.

THE ULTIMATE HARDNESS NUMBER.

In the author's formula the term z , which equals

$$\sqrt{D^2 - \left(\frac{L}{a}\right)^{\frac{2}{n}}}$$

merits further consideration. It decreases as L increases, and eventually becomes zero when

$$D^2 = \left(\frac{L}{a}\right)^{\frac{2}{n}}$$

i.e. when $D = \left(\frac{L}{a}\right)^{\frac{1}{n}}$, or $L = aD^n$.

At greater loads than this the term z becomes the square root of a minus quantity—that is, hardness measurement has ceased to be the function of the mechanical operation.

It has been suggested by O'Neill and Thompson¹ that under these conditions the ball will be forced continuously through the metal. This consideration may be of importance in connection with any operation involving penetration of the material. The formula indicates a final state of affairs in the specimen under the conditions obtaining in the Brinell test.

When the final load has been reached, the expression gives a value of H which, since $L = aD^n$, is independent of the load. Actually

$$\begin{aligned} H_u &= yLx = \frac{2a^{\frac{2}{n}}}{\pi} \cdot (aD^n)^{1-\frac{2}{n}} \\ &= \frac{2a}{\pi} \cdot D^{n-2}. \end{aligned}$$

It is suggested that this value of H might be called the "ultimate hardness" (H_u), and that it is a fundamental property associated with the disruption of the material. It is the hardness number when the ball is immersed up to its full diameter, and is easily calculated if a and n are known. These two quantities may be obtained by making impressions in the metal at two different loads. Tables could be prepared which would actually give H_u

¹ *Nature*, December 9, 1922, p. 773.

directly from readings of the two loads and their respective impression diameters.

Since

$$L_u = aD^n \text{ and } H_u = \frac{2a}{\pi} \cdot D^{n-2}$$

then

$$\frac{H_u}{L_u} = \frac{2}{\pi D^2} \text{ or } H_u = \frac{2}{\pi D^2} \cdot L_u.$$

Thus for any given ball diameter D , H_u , and L_u have a constant linear relation. In the case of the 10-millimetre ball

$$H_u = 0.006366 \cdot L_u.$$

It would be interesting to know to what extent the machining qualities of a metal depended upon this "ultimate hardness" value, previous work having shown that the ordinary Brinell number is of little use as a measure of machinability.

THE MAXIMUM BRINELL NUMBER.

From the formula given on p. 345, Mr. P. R. Ansell, B.A., has worked out expressions for H and L when the maximum occurs in the load-hardness curves. Reference to Appendix III. will show that

$$H_{\max.} = \frac{2a}{\pi} \cdot D^{n-2} \cdot \frac{n}{n-1} \cdot \left\{ \frac{n(n-2)}{(n-1)^2} \right\}^{\frac{n-2}{2}}$$

and the corresponding

$$L_{\max.} = aD^n \left\{ \frac{n(n-2)}{(n-1)^2} \right\}^{\frac{n}{2}}.$$

Thus knowing a and n one can calculate the maximum Brinell number and the load at which it occurs. These values have been worked out for some of the steels examined in this paper.

TABLE X.— $D = 1$ millimetre.

Steel.	a .	n .	$H_{\max.}$	$L_{\max.}$	H_u .	L_u .
2N	112	2.185	117	28.7	71	112
A	150	2.247	152	47.1	96	150
S90	264	2.298	260	93.8	168	264
W	323	2.312	316	118.2	206	323

TABLE XI.—D = 10 millimetres.

Steel.	a.	n.	$H_{\max.}$	$L_{\max.}$	$H_u.$	$L_u.$
A	74	2.288	142	4,993	91	14,360
W	185	2.292	358	12,710	231	36,240
4	262	2.292	507	18,000	327	51,320
3	342	2.293	663	23,540	428	67,140

From these tables it appears that :

The harder the material "naturally," i.e. due to chemical composition or heat treatment, the greater are the values of

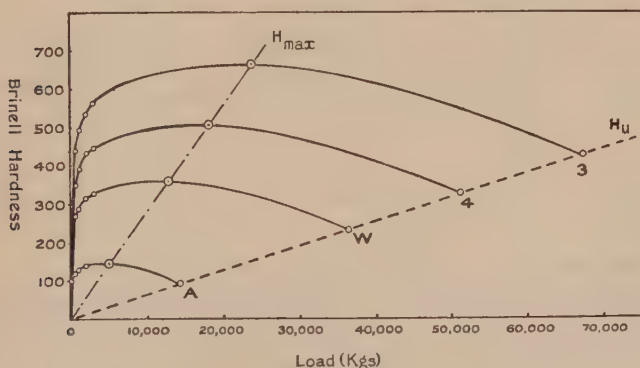


FIG. 5.—10-Millimetre Ball. Maximum and "Ultimate" Brinell Numbers.

$H_{\max.}$, $L_{\max.}$, H_u , and L_u . The maximum in the load-hardness curves is being moved to the right and upwards as the "natural" hardness increases. The results for the four steels tested with the 10-millimetre ball are plotted in Fig. 5, the values of H_u lying on a straight line passing through the origin.

TESTS ON SOFT METALS.

A sample of tin, one of lead, and one of zinc were cast into heated iron moulds. The intention was to test the unpolished cast surfaces with a 10-millimetre ball in the small Brinell machine, but it was necessary to give the zinc ingot a preparation with

0 emery-paper. The impressions were made not less than one week after casting, and the full load was steadily applied and maintained for two minutes. In some cases the impressions were inclined to be uneven, and the different readings were averaged.

The results are given in Table XII., and in addition the zinc was tested at 500 kilogrammes on the Alpha machine, giving impressions of 3.96 millimetres diameter. This corresponds to a Brinell number of 38.9.

TABLE XII.

Metal.		Load in Kilogrammes.					
		10	20	30	40	50	59
Lead . . .	<i>d</i>	1.74	2.25	2.70	3.12	3.35	3.66
("Pure"). .	H	4.17	4.96	5.13	5.08	5.50	5.41
Tin (99.85) .	<i>d</i>	1.33	1.80	2.17	2.48	2.74	2.98
	H	7.10	7.80	8.01	8.16	8.30	8.26
Zinc . . .	<i>d</i>	...	...	1.11	1.26	...	1.50
("Chem. Pure")	H	...	...	30.9	32.0	...	33.2

These results have been plotted logarithmically in Fig. 6. It will be observed that their accuracy is not such as will permit of a very reliable determination of the index n by this graphical method. Further values for these metals are given in Table XIV.

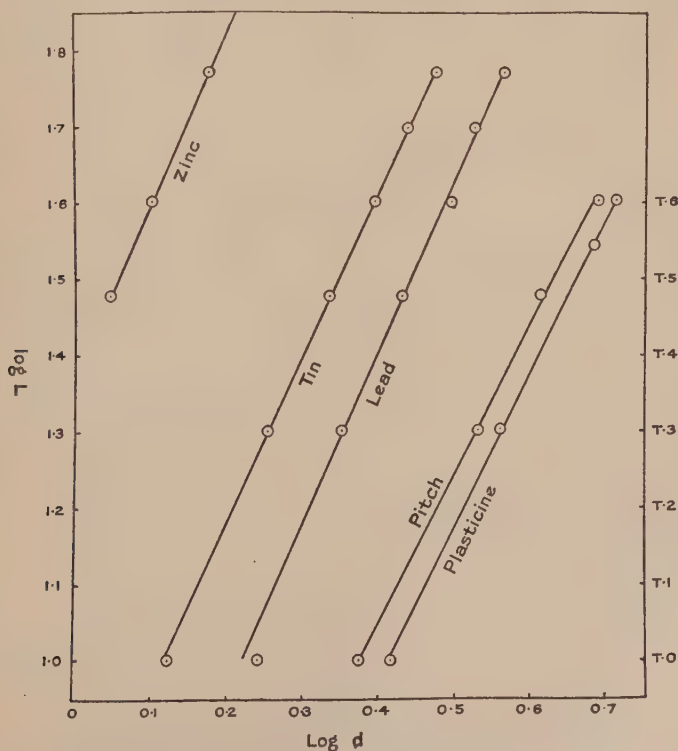
TESTS ON VISCOUS MATERIALS.

As examples of non-crystalline substances, pitch and plasticine were tested with a 10-millimetre ball. A lump of the former was cast into a rectangular slab and tested next day on the small Brinell machine. For the plasticine a small balance was constructed, beneath one pan of which the ball was fixed. The latter and its holder were counterpoised, and weights were placed in the pan above the ball. The loaded sphere was gently allowed to come into contact with the smooth surface of a slab of plasticine by manipulating the other arm of the balance. The full load was maintained for two minutes and then steadily removed, the pan being given a careful twist during this time to prevent the ball

from sticking to and dragging the plasticine. Care was taken that the temperature of the materials did not rise by too much handling and other causes, and the readings were taken immediately after indenting.

TABLE XIII.—*Viscous Materials, 10-millimetre Ball.*

Load in Kgs.	Pitch.				Plasticine.			
	10	20	30	40	0.10	0.20	0.35	0.40
<i>d</i>	2.36	3.39	4.10	4.87	2.60	3.62	4.83	5.15
H	2.26	2.14	2.17	2.01	0.0185	0.0188	0.0179	0.0178

FIG. 6.— $L = ad^n$. 10-Millimetre Ball.

From the graphs in Fig. 6 the value of n has been determined, and in both cases it is 2.0 within the limits of experimental error. This figure has been used for calculating the values of $H_{\max.}$ and $L_{\max.}$ in Table XIV.

TABLE XIV.—*Calculated Values. (Duration of Load, two minutes.)*

Material.	n .	a .	H_u .	L_u .	$H_{\max.}$	$L_{\max.}$
Plasticine . .	1.99	0.015	0.010	1.5	0.019	0
Pitch	1.96	1.83	1.17	167	2.3	0
Lead	2.26	3.18	3.68	579	5.8	188
Tin	2.185	5.53	5.39	847	8.8	217
Zinc	2.21	24.0	24.8	3890	40.1	1093

From the results in Table XIV. the complete curves for these materials have been drawn in Fig. 7.

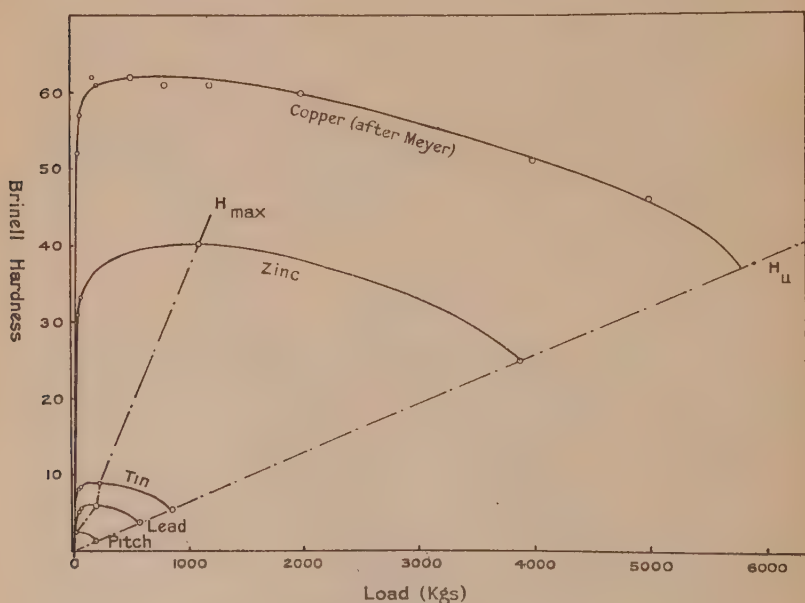


FIG. 7.—10-Millimetre Ball.

In connection with these soft metals the results obtained by Meyer⁽¹⁾ for copper over a long range of loads may be quoted

as confirming the general shape of the hardness-load curve. In Table XV. the Brinell numbers have been worked out for his different indentations and the values are plotted in Fig. 7.

TABLE XV.

Load.	Meyer's Copper (1).		Britannia Metal.	
	<i>d.</i>	H.	<i>d.</i>	H.
30	0.857	52	...	...
49	1.041	57	...	...
160	1.801	62	...	...
200	2.042	61	3.55	19.5
300	...	...	4.30	19.7
400	...	...	4.98	19.2
500	3.174	62	5.70	17.9
750	...	...	6.90	17.3
800	4.006	61	...	...
1200	4.841	61	...	...
2000	6.184	60	...	...
4000	8.635	51	...	...
5000	9.530	46	...	...

The second part of the table refers to a sample of "slowly cooled" Britannia metal tested by Thompson and Orme.⁽¹⁰⁾ Only the diameters of the impressions are reported in their paper. Hanriot's ⁽⁴⁾ tests on lead with an 18-millimetre ball give Brinell numbers rising from 3.9 to 4.5 as the load increases from 200 to 600 kilogrammes. But the hardnesses at 700 and 800 kilogrammes are 4.0 and 4.1 respectively.

Perhaps the most interesting conclusion in this section of the work is that viscous materials have a Brinell number which falls continuously with increase of testing load, and their value for n is 2.0. This being so, the constant a becomes of special interest.

If $a = \frac{L}{\bar{d}^n}$, then taking physical dimensions of this relation

$$[a] = \left[\frac{\text{Mass}}{\text{Length}^n} \right]$$

i.e., a is not independent of n .

When $n = 2.0$

$$[a] = \left[\frac{\text{Mass}}{\text{Length}^2} \right]$$

i.e., a is a stress.

THE EFFECT OF COLD-WORK ON $H_{\max.}$ AND H_u .

Several workers ^(2, 5, 6) have shown that as a material is cold-worked the value of n decreases and would eventually become 2.0. From the expression given on p. 354, it will be found that when $n = 2.0$, $H_{\max.} = \frac{4a}{\pi}$ and $L_{\max.} = 0$. If the material be cold-worked to a smaller extent, so that n is greater than 2.0, then $H_{\max.}$ will be smaller than before and will occur at a higher load.

An investigation by Baker and Russell,⁽⁶⁾ carried out with great care and thoroughness, provides data for confirming these deductions. In their work, test-pieces Numbers 1, 2, 3, and 4 of the same mild carbon steel No. 0 were cold stressed to increasing amounts and the values of a and n determined. In Table XVI. their figures have been used to calculate the other values under consideration.

TABLE XVI.—*Baker and Russell's Cold-Worked Steel.*

Sample No.	a .	n .	$H_{\max.}$	$L_{\max.}$	H_u .	L_u .
0	70.0	2.293	136	4820	88	13,750
1	79.7	2.236	139	4181	87	13,730
2	91.6	2.185	147	3600	89	14,030
3	98.9	2.147	150	3003	88	13,870
4	113.6	2.095	158	2156	90	14,140

All the available figures have been plotted in Fig. 8, and the theoretical curve has also been drawn for when $n = 2$ in this material.

We may conclude that, as the cold-work upon this steel increases, then for the given ball diameter :

(1) n decreases to 2.0 ; a being then $\frac{L_u}{D^2}$, equals 139.

(2) $H_{\max.}$ increases until $n = 2.0$, when $H_{\max.} = \frac{4a}{\pi} = 177$.

(3) $L_{\max.}$ decreases and becomes zero when $n = 2.0$.

(4) H_u and L_u remain practically unaffected.

With regard to the last observation, it appears that the small variation in the values of H_u and L_u could easily be accounted for by a slight experimental error in the determination of n . The fact that the variations occur in no set order suggests that

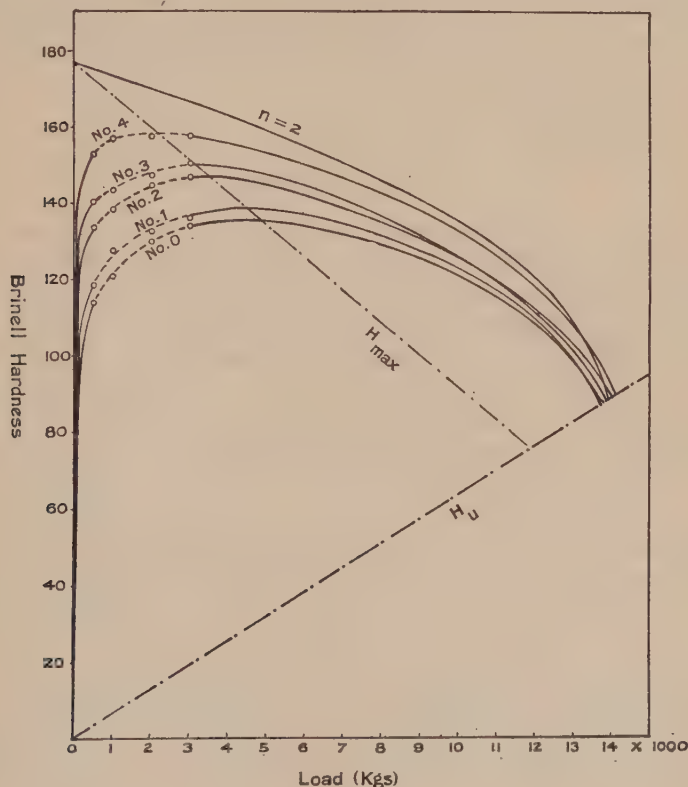


FIG. 8.

this is the case, and we may conclude that H_u and L_u remain constant.

This suggests that as L_u is the load at which a 10-millimetre ball passes through the metal, then cold-working that metal would not increase its resistance to perforation.

We may say that the effect of cold-work is to cause the maximum in the load-hardness curve to be moved upwards and to the left until it coincides with the vertical axis when $n = 2.0$.

Baker and Russell's Brinell tests on each bar were made with loads increasing from 500 to 3000 kilogrammes. They note that the resulting load-hardness graphs "display very clearly the effect of cold-work in flattening out the curve." What they actually observed was the approach of that flat portion of the curve which occurs at H_{\max} . In Specimen 4 they have actually got up to the maximum, since theoretically it falls between the testing loads used by them.

THEORETICAL CONSIDERATIONS.

The rise of Brinell number with increase of testing load has usually been ascribed to the greater cold-hardening of the metal at the higher pressures. That the hardness number eventually falls is not necessarily in conflict with this idea.

Heyn⁽¹²⁾ has shown that the ball-pressure hardness of copper decreases after a certain amount of cold-work has been put upon the metal. The scleroscope hardness of the low-tin bronzes investigated by Alkins and Cartwright⁽¹³⁾ first rises as the alloys are cold-drawn, and then proceeds to fall after a certain stage of reduction. Ingall⁽¹⁴⁾ found that the Brinell number of zinc decreased after a percentage reduction in the cold of 92. Samples of silver were cold-rolled by Hanriot⁽⁴⁾ to increasing extents, and their Brinell hardness was measured. Test-pieces made from those samples *which had received most rolling* were broken in tension. It was found that the resulting increase in cold-work had caused a decrease in the Brinell number of those samples. Similar results were obtained with aluminium and with brass. It appears, therefore, that the stress required to produce an indentation in a metal increases as that metal is cold-worked. But the rate of increase becomes progressively smaller, and in the case of the metals mentioned, passes through a zero value and actually becomes negative. This state of affairs may be related to the "critical ranges" found during many cold-drawing operations.

The decrease in Brinell number observed by Jeffries,⁽¹⁶⁾ Fry and Rosenhain,⁽¹¹⁾ and others, after cold-working certain soft metals, is in agreement with the idea of a critical amount of deformation, beyond which the metal changes its properties. Although they found that hammered tin had a lower Brinell

number than the sample as cast, yet even with the ordinary method of loading, tin can show an increase in Brinell hardness after cold-rolling. Further experiments are being carried out in this direction.

It has been shown that the value of Meyer's n for a viscous material is 2.0, whilst that for a metal is known to approach 2.0 as it is cold-worked. This is of significance in connection with the theory that amorphous material is formed and accumulated as a crystalline aggregate undergoes deformation in the cold.

CONCLUSIONS.

1. The curve showing the relation between the indenting load and the resulting Brinell number commences at the origin and rises steeply at first. It then flattens out and passes through a maximum, subsequently falling until the ball is embedded in the specimen.

2. The Brinell number is the sum of two terms, the second of which is equal to the first multiplied by a factor. This factor decreases in value from 1.0 to zero as the testing load increases over the range of the test.

3. Up to the maximum in the load-hardness curve this factor is of such a value as to permit of the following approximate relation :

$$H = KL^x.$$

4. The curve ends when the ball is immersed up to its diameter in the metal. The Brinell number and load corresponding to this point have been called the "ultimate hardness" and the "ultimate load" respectively. There is a linear relation between the two for all metals.

5. The harder the material the higher the maximum value of the Brinell number and the greater the load at which it occurs.

6. Viscous materials obey Meyer's formula and have a value for n of 2.0. Their Brinell number is a maximum when $L = 0$, and decreases as the testing load increases.

7. The effect of cold-work upon a metal is to raise the maximum Brinell number and to decrease the value of the load at which it occurs. The "ultimate hardness" and the "ultimate load" appear to remain constant.

8. It is probable that after a certain amount of deformation in the cold the rigidity of a metal decreases.

In conclusion, the author wishes to thank Professor F. C. Thompson for help and advice given throughout the course of the work. He is particularly indebted to Professor C. H. Desch for kindly interest, and for permission to use the apparatus at the University of Sheffield. His thanks are also due to Messrs. J. Cartwright, P. R. Ansell, and H. Wright Baker for assistance in various ways.

APPENDIX I.

The values for load and diameter recorded on p. 348 for four steels tested with the 10-millimetre ball have been plotted logarithmically. The points all lie on straight lines, thus confirming Meyer's formula under these conditions. The values for a and n were found to be as follows :

TABLE XVII.— $L = ad^n$ with the 10-millimetre Ball.

Steel.	Brinell No. at 3000 Kgs.	a .	n .
A	140	74	2.288
W	327	185	2.292
4	444	262	2.292
3	564	342	2.293

The results obtained with a ball of 1 millimetre have been plotted logarithmically in Fig. 9.

Straight lines can be drawn through the points corresponding to loads of 5, 10, 20, and 30 kilogrammes, but the remaining two points are to the right of this line except in the case of Armco. The graphs gave the following values :

TABLE XVIII.— $L = ad^n$ with the 1-millimetre Ball.

Steel.	Brinell No. at 30 Kgs.	a .	n .
Armco	103	94	2.164
2N	112	112	2.185
A	149	150	2.247
S90	264	264	2.298
W	323	323	2.312

It appears that with a ball of unit (1 millimetre) diameter the value of a —for the above materials at least—equals the

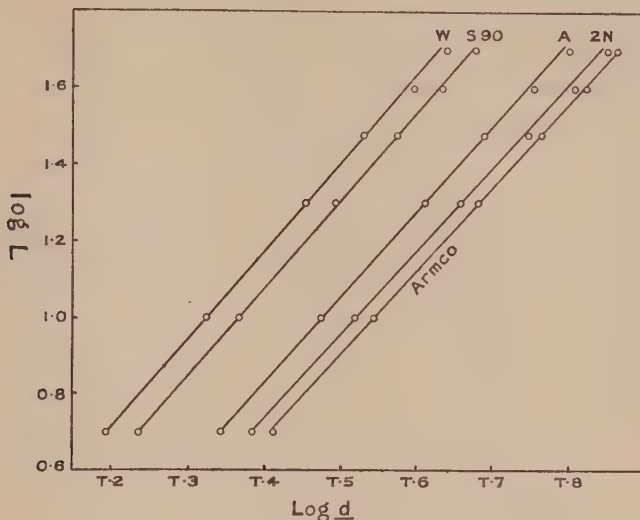


FIG. 9.— $L = ad^n$. 1-Millimetre Ball.

Brinell number at 30 kilogrammes. This means that both a and n could be obtained from the one impression at that load.

If the value of n is not quite constant over all ranges of load, then the calculated values of L_{\max} and L_u , given earlier in this paper, may differ from those obtained experimentally.

APPENDIX II.

BRINELL HARDNESS AND SCLEROSCOPE HARDNESS.

Many attempts have been made to find a relation between the Brinell number and the scleroscope number. Shore⁽⁷⁾ made use of a very large number of materials and tested them with a 10-millimetre ball at a load of 750 kilogrammes. Since bulging of the loaded ball gives low Brinell numbers, a diamond was used for indenting the very hard specimens. The Shore numbers were plotted against the Brinell numbers and a smooth average curve was drawn.

This paper provides data for obtaining the Brinell numbers at 3000 kilogrammes and at 750 kilogrammes for steels of different hardnesses. In this way a curve for the standard Brinell values can be built up on Shore's relation curve.

The following table was drawn up by interpolating the various load-hardness curves at 750 kilogrammes. The scleroscope number of each specimen was also determined.

TABLE XIX.

Specimen.	Brinell No. at 750 Kgs.	Brinell No. at 3000 Kgs.	Actual Shore No.	Shore No. from Curve.
A	125	140	27	25.0
S90	225	264	41	44.5
W	278	327	51	53.5
4	374	444	64	67.5
3	472	564	73	79.0

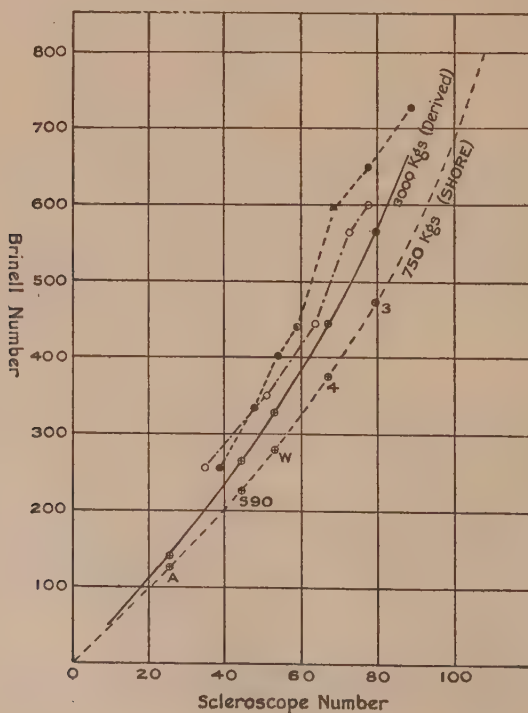


FIG. 10.

In Fig. 10 points have been marked along Shore's curve corresponding to the Brinell numbers at 750 kilogrammes of the specimens reported in Table XIX. Vertically above these points the Brinell value at 3000 kilogrammes has been plotted. In this way the curve marked "3000 kilogrammes (derived)" has been obtained.

If there be a true relation one can obtain from the latter curve the scleroscope values corresponding to standard Brinell numbers. Such scleroscope values are given in the last column of Table XIX. for the specimens under consideration. They are higher than those obtained experimentally. (It should be mentioned that samples 4 and 3 were 2-inch lengths of $\frac{1}{2}$ -inch square bar, and the actual scleroscope numbers may be about two units low because of the somewhat small size.)

To further test this relation curve two series of heat-treated steels were examined. The results obtained with surfaces finished on 000 emery-paper are given in Table XX.

TABLE XX.—*Steel D: Carbon, 0.95 per Cent.; Chromium, 4.19 per Cent. 1-inch Cubes.*

Specimen No.	Brinell No. at 3000 Kgs.	Actual Scleroscope No.
4	255	39
5	333	48
9	401	54
7	438	59
10	594	69
11	648	78
Q	726	89
<i>0.9 per Cent. Carbon Steel, $\frac{1}{2}$-inch Square Bar.</i>		
2	600	78
3	564	73
4	444	64
5	351	51
R	255	35

These results have been plotted in Fig. 10 and the points joined by straight lines. They do not agree well with the derived relation curve. Figures put forward by Rockwell⁽¹⁷⁾ for the Brinell hardnesses corresponding to various scleroscope numbers do, however, agree with it fairly satisfactorily. But under the

author's conditions there does not seem to be any true relation between scleroscope and Brinell hardnesses.

It is perhaps unlikely to expect such a relation when one considers the very arbitrary nature of the two tests. Then, again, the physical dimensions of the two systems are different.

That of the Brinell method is $\left[\frac{\text{Mass}}{\text{Length}^2} \right]$, whilst the Shore hardness is a height of rebound having a dimension in $[\text{Length}]$ only.

APPENDIX III.

Expressions for H_{max} . and L_{max} .

It has been shown (p. 345) that

$$H = \frac{2a}{\pi D} \left\{ \frac{L}{a} \right\}^{(1-\frac{2}{n})} \left[D + \sqrt{D^2 - \left(\frac{L}{a} \right)^{\frac{2}{n}}} \right]$$

where $n > 2$.

The formula is obviously valid only for the range

$$0 \leq L \leq aD^n.$$

\therefore We may write $L = aD^n \sin^n \theta$ where $0 \leq \theta \leq \frac{\pi}{2}$.

$$\begin{aligned} \text{Then } H &= \frac{2a}{\pi} D^{n-2} \sin^{n-2} \theta [1 + \cos \theta]. \\ \frac{dH}{d\theta} &= \frac{2a}{\pi} D^{n-2} \sin^{n-3} \theta [(1 + \cos \theta) (n-2) \cos \theta - \sin^2 \theta] \\ &= \frac{2a}{\pi} D^{n-2} \sin^{n-3} \theta [\overline{n-1} \cos^2 \theta + \overline{n-2} \cos \theta - 1]. \\ \frac{d^2H}{d\theta^2} &= \frac{2a}{\pi} D^{n-2} \sin^{n-4} \theta [(n-3) \cos \theta \{ \overline{n-1} \cos^2 \theta \\ &\quad + \overline{n-2} \cos \theta - 1 \} - \sin^2 \theta \{ 2(n-1) \cos \theta + n-2 \}]. \end{aligned}$$

\therefore The maxima and minima, apart from the minimum given by

$$\left. \begin{matrix} \theta = 0 \\ L = 0 \end{matrix} \right\} H = 0, \text{ correspond to values of } \theta \text{ agreeing with } \frac{dH}{d\theta} = 0, \text{ i.e.}$$

$$\begin{aligned} (n-1) \cos^2 \theta + \overline{n-2} \cos \theta - 1 &= 0 \\ [(n-1) \cos \theta - 1] [\cos \theta + 1] &= 0. \end{aligned}$$

$$\therefore (a) \cos \theta = \frac{1}{n-1}$$

or (b) $\theta = \pi$, which is outside the range.

$$\begin{aligned} (a) \text{ gives } \frac{d^2 H}{d\theta^2} &= \frac{2a}{\pi} D^{n-2} \sin^{n-4} \theta [-n \sin^2 \theta] \\ &= -\frac{2an}{\pi} D^{n-2} \sin^{n-2} \theta, \end{aligned}$$

which is negative.

$\therefore \cos \theta = \frac{1}{n-1}$ corresponds to a maximum of H .

The corresponding value of $\sin \theta$ is

$$\sin \theta = \sqrt{\frac{n(n-2)}{n-1}}.$$

$$\therefore H_{\max.} = \frac{2a}{\pi} D^{n-2} \frac{n}{n-1} \left\{ \frac{n(n-2)}{(n-1)^2} \right\}^{\frac{n-2}{2}},$$

corresponding to

$$L_{\max.} = a D^n \left\{ \frac{n(n-2)}{(n-1)^2} \right\}^{\frac{n}{2}}$$

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- (16) JEFFRIES, Z.—“The Amorphous Metal Hypothesis.” *Journal of the American Institute of Metals*, 1917, vol. xi., No. 3.
- (17) ROCKWELL.—*Transactions of the American Society for Steel Treating*, August, 1922.

The attention of the author has been drawn by Sir Robert Hadfield to the following papers which it is perhaps desirable to include although the references in the present paper are confined to the earlier list, and the preceding bibliography is not put forward as being in any sense exhaustive.

LIST OF PAPERS ON HARDNESS

Read before the Institution of Mechanical Engineers.

	<i>Proceedings.</i>
“Report of the Hardness Tests Research Committee”	1916, p. 677
“Testing Hardness of Metals” (Boyelle-Morin Apparatus). By C. J. BOWEN COOKE, C.B.E.	1918, p. 331
“Law Governing the Resistance to Penetration of Metals when Tested by Impact with a 10-mm. Steel Ball, and a new Hardness Scale in Energy Units.” By Professor C. A. EDWARDS and F. W. WILLIS	1918, p. 335
“Value of the Indentation Method in the Determination of Hardness.” By R. G. C. BATSON	1918, p. 463
“Ludwik Hardness Test.” By W. C. UNWIN	1918, p. 485
“Note on Brinell and Scratch Tests for Hardened Steel.” By Sir ROBERT HADFIELD, Bart., and S. A. MAIN	1919, p. 581
“Prism Hardness.” By B. P. HAIGH	1920, p. 891
“Measurement of High Degrees of Hardness.” By J. INNES	1920, p. 915
“Hardness Testing.” By H. S. PRIMROSE and J. S. G. PRIMROSE	1920, p. 933
“Small Ball-Hardness Testing Machine.” By H. MOORE	1921, p. 51
“An Accurate Method of Determining the Hardness of Metals, with Particular Reference to those of a High Degree of Hardness.” By R. L. SMITH and G. E. SANDLAND	1922, p. 623

DISCUSSION.

Dr. C. A. EDWARDS (Swansea) asked what Mr. O'Neill really meant by his ultimate hardness figure. Did he really mean that the hardness of a metal after it had passed a certain minimum value of diameter became less with further penetration, and then became so low that the ball proceeded to go through the material without additional pressure? If that was what Mr. O'Neill really did mean, he thought he had omitted the work hardening factor; because, so far as he himself had been able to test it, plastic flow could never be made to proceed to such a degree. It always came to a dead rest, with the possible exception, it might be, of a metal like lead. Lead might conceivably go on flowing under such conditions, but in all other metals with which he himself and his colleagues had experimented with, it certainly did not take place.

Mr. A. S. E. ACKERMANN (London) said an extremely interesting fact had been predicted by Mr. Hugh O'Neill in *Nature*, and repeated at p. 345 of his present paper, as the result of combining the hardness equations of Brinell and Meyer, namely, that if the load on the ball attained a certain critical value, $L = aD^n$, the ball would continue sinking into the plastic material under tests without further increase of load. The load which caused that he had called L_u , and the resulting value of the hardness he had called H_u . He (Mr. Ackermann) had been delighted to see that letter in *Nature*, and wrote a couple of days afterwards to that paper pointing out that what Mr. O'Neill had so cleverly predicted by means of his formula had in fact been obtained as an experimental result by himself in the case of clay and a lead-tin alloy, and that he had called the critical stress at which it occurred the "pressure of fluidity." On comparing the results given by Mr. O'Neill's equation and those he had himself obtained, it was found that the latter were exactly double those given by the former. The explanation was that Brinell and Meyer divided the load by the area of the curved surface of the ball, whereas in the case of the pressure of fluidity it was the projected area of the ball or disc which was used, and in the case of the ball completely embedded in the material under test the projected area was exactly half the area of the curved surface of the hemisphere.

Since then he had, with the generous assistance of Mr. R. H. H. Stanger, experimentally determined the pressures of fluidity of lead, tin, aluminium, and copper, and on plotting the curves connecting the load and penetration they were found to be of exactly the same character as those for clay; in fact, if the scales were suitably altered

the same curves would do for either clay or the various metals. Thus, Mr. O'Neill's prediction had been entirely justified, namely, that there was a certain critical load which on being attained caused the ball to continue to sink into the plastic metal without further increment of load.

He (Mr. Ackermann) had not, in fact, used a ball for the metals, but a punch 10 millimetres in diameter with a shank 9 millimetres in diameter, as he had previously found in the case of clay that it did not matter whether he used a sphere of a particular diameter or a duralumin disc of exactly the same diameter. Both gave the same value for the pressure of fluidity, the reason apparently being that, in the case of the disc, there was a stagnant cap of clay which went down with the disc, and consequently acted more or less as a hemisphere. That fact was experimentally determined.

He had recently published, in a paper before the Society of Engineers,¹ an hypothesis to account for the phenomenon of the pressure of fluidity in the case of clay, and it was remarkable that it was found to apply to plastic metals even better than to clay as far as it had been tested in the case of the latter. That hypothesis was far too elaborate to give then, but the final result was very simple, namely, that $p = 3.68c + 5.21f$, where p = the pressure of fluidity, c = the cohesive or tensile strength of the material, and f = the shearing strength (all in kilogrammes per square centimetre). The results given by that equation were not identical with the experimental ones, but were consistently 30 per cent. in excess, implying that some factor had been left out of account. Probably the explanation was that the specimens used for the determination of the pressure of fluidity were only 70 millimetres in diameter and bulged slightly under test due to the displacement of the metal by the punch. If the specimens had been larger in area, it was reasonable to suppose that the additional lateral resistance to the flow of the metal from under the punch would have increased the experimental values of the pressure of fluidity, and thus have made the difference between the calculated and actual values less. As, however, the difference was constant within the degree of variation of the values of c and f , which were experimental results, it was comparatively unimportant that there was that constant difference.

It was also to be noted that the range over which the hypothesis had been tested in the case of plastic metals was no less than from 777 kilogrammes per square centimetre (the experimental value of the pressure of fluidity of lead) to 10,860 kilogrammes per square centimetre, the corresponding value for copper.

¹ March 5, 1923.

CORRESPONDENCE.

SAMUEL L. HOYT, Ph.D., Member (Schenectady), wrote that he was greatly interested in the author's paper as a further attempt to elucidate the true character and meaning of the Brinell ball hardness test. He thought, however, that the author had got into difficulties owing to his use of the Brinell hardness number as a physical constant, and he (Mr. Hoyt) called attention, in that connection, to several important points brought out by Meyer in the work referred to by the author. The Brinell number varied in an unwarranted manner with the pressure, due to the geometry of the impressions and not to the characteristics of the metal tested, and actually passed through a maximum at some value of d , $= d_0$. For a ball diameter, $D = 10$ millimetres, that maximum ($H_{\max.}$) was as follows :

	for $n = 2$	2.1	2.2	2.3	2.4
$H_{\max.}$ comes at $d_0 = 0$		4.17	5.53	6.39	7.00

The Brinell hardness number had no true physical significance, and its use led to irregularities which did not reflect actual physical characteristics of the metal tested. It might be asked, "Why did Brinell adopt such a hardness number?" The writer believed that Brinell was looking merely for some arbitrary number for the expression of the ball hardness and was not greatly concerned with the variation of his number with the pressure, and he standardised on 500 and 3000 kilogrammes. Realising that the superficial area of contact between the ball and the sample varied more rapidly than the projected area of the impression up to an impression angle of 45° , he selected the former area to get a more open scale than the latter would give. He then selected loads (3000 kilogrammes for hard metals and 500 kilogrammes for soft metals) which would give sizable impressions, but which would not produce an impression angle of more than 45° . That impression angle was the angle between the centre of the ball when in place and the rim of the impression. It was doubtful if Brinell subjected his method to rigid analysis, which was done for the first time by Meyer.

Professor Meyer, realising that the hardness number adopted by Brinell was not suited to rigid interpretations of the hardness (for example, for comparing different metals quantitatively as to hardness or the hardness of a given metal at different loads), used the true mean pressure between the ball and the specimen,

$$P_m = \frac{P}{\frac{\pi d^2}{4}}$$

In the light of Meyer's work it would be extremely difficult to discuss the author's paper, for it would continually be necessary to

distinguish between variations in actual hardness and variations due to the use of Brinell's hardness number. It was true that the paper, by title, dealt with the variation in Brinell hardness number and not necessarily with the hardness, but the author evidently believed he was dealing with hardness and not with geometry. He even saw a connection between the fall in Brinell hardness number past H_{\max} and the drop in hardness in very severely worked metals. As a matter of fact, there was good evidence that beyond a certain point in cold working the metal actually became softer to the Brinell and scleroscope tests, but the evidence came from comparing the hardness at constant load of two samples representing different amounts of work. That was quite a different matter from comparing the same metal at different pressures. As a matter of fact, between the limits of $d = 1$ millimetre and $P = 5000$ kilogrammes, the hardness of a metal actually varied with increase in load. It increased if $n < 2.0$ and decreased if $n = 2.0$ as had been shown by Meyer.

According to that discussion the author's conclusions should be interpreted as applying simply to the Brinell hardness number and not at all to the actual resistance to penetration or penetration hardness.

Mr. T. F. RUSSELL wrote that Mr. O'Neill's paper contained many interesting points, not the least being his determination of Meyer's index n for plasticine. The value $n = 2$ might be anticipated on theoretical grounds. Plasticine should be described as a plastic substance rather than a viscous one. Theoretically, the Brinell number of a viscous substance could not be determined, as its value decreased progressively with time; therefore the results obtained with pitch were less convincing.

On p. 362 Mr. O'Neill referred to Baker and Russell's "load-hardness" graphs, but he would find that those were called "Brinell No. load" and "Ball No. load" graphs, for he (Mr. Russell) wished to dissociate the word hardness from the Brinell test.

In several portions of Mr. O'Neill's paper the terms "Brinell number" and "Hardness number" were used synonymously, and led to much confusion. It was therefore all the more unfortunate that the name "ultimate hardness" had been given to H_u —the Brinell number when the ball was immersed up to its full diameter. As the "ultimate hardness" was less than the "maximum hardness," the impression was created that the hardness of steel passed through a maximum when a certain amount of cold work was done upon it and decreased with further cold work. That appeared to be Mr. O'Neill's view, for in Conclusion 8 he wrote: "It is probable that after a certain amount of deformation in the cold the rigidity of a metal decreases." That, of course, was not true. All steels were progressively—but at a diminishing rate—hardened by cold work.

The Brinell test was of inestimable commercial value; but as a means of investigating the hardening properties of metals it was

very crude. On p. 353 it was suggested that H_u , the "ultimate hardness," was a fundamental property, but the equation immediately above that statement showed that H_u was dependent on D , the diameter of the ball, and could not be a measure of a fundamental property. Mr. O'Neill would probably have noticed that on p. 359, and again on p. 368, the dimensions of a stress were originally incorrectly given.

Mr. O'NEILL wrote in reply that many of the points raised by those gentlemen who had been good enough to discuss the paper centred round the difficulty of accurately and scientifically defining the term "hardness." The Brinell test had many shortcomings, but had become recognised commercially as a standard method of measuring "hardness." It therefore seemed desirable to investigate fully its character, and if it suffered in the process, then everyone was so much the wiser. For example, the investigation had shown that the expression $H = K + L^x$ was erroneous. That meant that that portion of Mr. F. Harris's interesting work¹ on hardness based upon that expression now needed revision. He had simply accepted the Brinell test and then, as Dr. Hoyt mentioned, had dealt in the paper with the variation in Brinell hardness number without inquiring whether that number really represented the hardness. That explanation might lessen the confusion which Mr. Russell found over the synonymous use of "Brinell number" and "hardness number."

In reply to Dr. Edwards, the name "ultimate hardness," as stated on p. 353, had been given to the Brinell hardness number obtained when the ball had been loaded just up to its diameter. The term was perhaps unfortunate, and "ultimate Brinell number" was suggested instead. The conclusion stated on p. 361 that that term appeared to be unaffected by cold work was based on the data of Baker and Russell. Later work of his (Mr. O'Neill's) own and the results of Meyer and Kurth suggested that H_u and L_u were increased slightly by cold work.

Mr. Ackermann's most interesting communication should clear up any doubts of Dr. Edwards as to whether a critically loaded indenting tool would continuously penetrate a metal. The bulging of the specimens used by Mr. Ackermann would affect the absolute values of his "pressures of fluidity," and for penetration experiments with a 10 millimetre tool quite a wide slab of metal appears to be necessary.

He (Mr. O'Neill) realised that the Brinell number varied with different angles of impression because of the geometrical dissimilarity of the impressions and the different degrees of strain-hardening produced. The wording used on p. 362 in reference to the form of the Brinell number-load curve and cold work effects was non-committal and undogmatic. Conclusion 8, dealt with by Dr. Hoyt and Mr. Russell,

¹ *Journal of the Institute of Metals*, 1922, No. 2.

was based on the evidence put forward on p. 362. In addition it might be mentioned that Schottky found that the tensile strength of gold leaf began to decrease when the reduction in thickness by cold work passed a certain limit.

The standard Brinell test on steels at 3000 kilogrammes and on materials like soft brass at 500 kilogrammes was carried out on the rising part of the Brinell number—load curve. Tests at 500 kilogrammes on much softer metals would occur past the maximum in the curve. For comparison purposes it was therefore suggested that a standard load of not more than 200 kilogrammes should be used for such materials, *e.g.*, white metals.

Iron and Steel Institute.

THE COLD-WORKING OF STEEL WITH REFERENCE TO THE TENSILE TEST.

By JOHN STEAD.

THE experiments described in this paper were originally undertaken with the object of finding some relation between the tensile strength of wire and that of the steel from which it was drawn. No definite relation was obtained, but some of the results are of interest from the point of view of cold-working generally. The data obtained are unfortunately meagre, as the investigation had to be stopped before it was complete, and there has since been no opportunity of continuing it. The data, however, are sufficient to justify qualitative conclusions. To obtain accurate quantitative values many more experiments would be required.

The experiments were to obtain the true stress-strain diagram from yield point to fracture of steel undergoing the ordinary tensile test, and from it to derive an equation connecting stress and strain. The diagram usually obtained for the tensile test is derived from load, and the extension between two arbitrarily chosen points on the test-piece. This diagram has no theoretical meaning, since the extension has no relation to the strain, except perhaps in the portion of the curve between the yield point and the maximum load. Even if an equation could be obtained for this curve, it would give very little information.

THE THEORY OF THE EXPERIMENTS.

The stress-strain diagrams were obtained by the method used by Baker and Russell¹ in their paper on the ball test. The stress is calculated from actual measurement of the diameter of the test-piece and the corresponding load while it is undergoing the test.

¹ *Journal of the Iron and Steel Institute*, 1921, No. I. p. 341.

The strain is not measured directly, but is calculated from the diameter. The piece is assumed to elongate without necking, the volume remaining constant. Any changes in volume that may occur are so small that they are well within the experimental error.

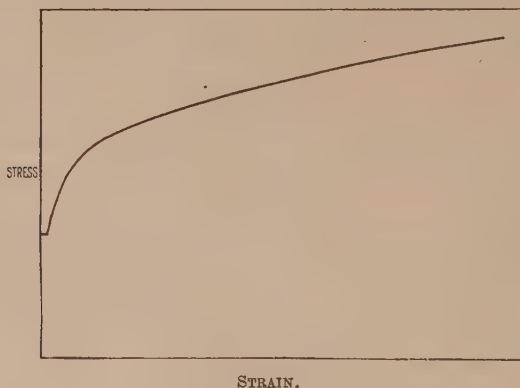


FIG. 1.

The strain is calculated thus :

If L be the original length, D the original diameter, and $L + l$ the length corresponding to any diameter d ,

$$\text{Volume of the piece:} \quad = \frac{\pi D^2}{4} \cdot L = \frac{\pi d^2}{4} (L + l);$$

$$\therefore \frac{D^2}{d^2} = 1 + \frac{l}{L}.$$

$$\text{The strain } x = \frac{l}{L} = \frac{D^2}{d^2} - 1.$$

Since this does not depend at all on the length L , the latter can be made as small as desired ; so small that on the test-piece, even when necking takes place, the sides will remain parallel for a length $L + l$. The stress-strain diagram obtained in this way gives the type of curve shown in Fig. 1. This curve cannot be made to fit any of the commoner types of equation.

If, however, instead of plotting the stress against the strain, it is plotted against the diameter of the piece, the type of curve obtained is shown in Fig. 2. This curve divides itself into two

portions, the end portion AB being a straight line and corresponding with an equation

$$P = a - bd \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where P is the stress, d the diameter, and a and b are constants.

The whole of the curve from the yield point to the breaking point can be represented by an equation of the form :

$$P = a - bd - e^{cd-f} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

c and f being constants.

In this equation the last part of the curve is not strictly a

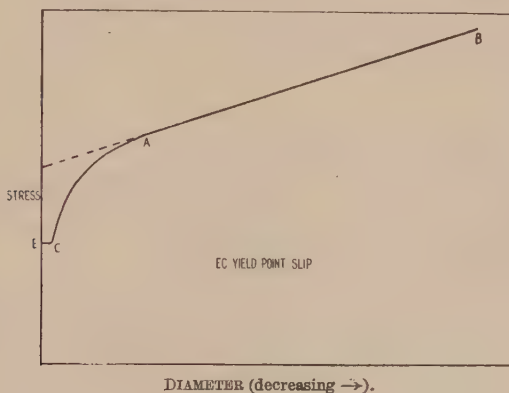


FIG. 2.

straight line, since equation (1) is the asymptote to equation (2), but for all practical purposes it may be considered straight, since although the term e^{cd-f} can never become zero, for all values of $d < \frac{f}{c}$ its value lies between 1 and 0, and so can be ignored.

From this equation the stress-strain equation can be derived immediately. Since the strain

$$x = \frac{D^2}{d^2} - 1$$

$$d = \frac{D}{\sqrt{1+x}}$$

So that the stress-strain equation is :

$$P = a - b'(1+x)^{-\frac{1}{2}} - e^{c'(1+x)^{-\frac{1}{2}}-f}$$

where $b' = bD$ and $c' = cD$.

If the original diameter of the piece be = 1, the stress-strain equation is :

$$P = a - b(1 + x)^{-\frac{1}{2}} - e^c(1 + x)^{-\frac{1}{2}} - f \quad . \quad . \quad (3)$$

That is, it is obtained from the stress-diameter equation by the simple substitution of $(1 + x)^{-\frac{1}{2}}$ for d .

As most of the information that can be deduced from this equation depends on the value of the constants a , b , c , and f , and since they are the same in both the stress-strain and the stress-diameter equations (provided the latter is calculated for an original diameter of 1), it is simpler for the most part to confine attention to the stress-diameter equation, since no assumptions have been made in obtaining it.

DETAILS OF THE EXPERIMENTAL METHOD.

The tests were made in an Olsen 50-ton machine. Two observers were required, one to measure the diameter, and the other to read the corresponding loads.

The diameters were measured by means of a micrometer reading to 0.0001 inch, the jaws of which were brought to a point, so that the diameter could be measured at the centre of the neck. The micrometer was set for regularly decreasing diameters, and when it just slipped over the test-piece the load was read. The diameter was always measured where it was a minimum.

The test-pieces, unless otherwise stated, were about 0.565 inch diameter and 7 inches long between the shoulders. They had usually screwed ends.

The diameter readings were taken every 0.001 inch from the yield point to 0.540 inch, and then every 0.005 inch until fracture. In some cases, after the diameter had decreased to 0.400 inch, the readings were taken every 0.01 inch.

The load was read to 5 lbs., and occasionally to 2.5 lbs. Since the jockey of the machine moves in jerks there is always a possible error in the reading of the load. This error was found to be regular, depending on the period of vibration of the lever of the machine. It represents a possible error of about 100 lbs. per square inch in the calculated stress.

In deducing the equations from the readings the following method was applied. The equation to the straight part of the curve was found by drawing a straight line as nearly as possible through the points. Owing to the possible error in the value of the stress, this method is quite accurate enough. The coefficient b could be determined with an accuracy of 0.2 per cent., and similarly for a .

The first part of the curve is obtained by subtracting the stress actually obtained from the value of the stress given by the equation: $P = a - bd$. The logarithms of the differences thus obtained were plotted against the diameters and a straight line drawn through the points. The coefficients c and f could thus be obtained with an accuracy of 0.2 per cent.

It will be seen that to derive the equation a considerable portion of the straight part of the curve must be obtained. This is the portion between the maximum load and the fracture. Thus it is not possible to obtain any accurate equations for the high carbon steels, as they do not give enough of the straight part of the curve to yield reliable results. All the equations given in this paper have been reduced to an original diameter of 1.

Only one test was done on each steel, unfortunately, so that it is impossible to tell how far the various constants obtained may vary for the same steel. From some experiments mentioned later, on some nearly identical steels, it would appear that the variation is not great, and certainly not as great as the variations in the yield point and the maximum stress.

DESCRIPTION OF STEELS USED AND THE HEAT TREATMENTS.

The following steels were used :

TABLE I.

Steel.	Carbon per Cent.	Silicon per Cent.	Sulphur per Cent.	Phosphorus per Cent.	Manganese per Cent.
1	0.16	0.10	0.029	0.019	0.47
2	0.28	0.153	0.057	0.055	0.73
3	0.34	0.141	0.050	0.058	0.72
4	0.44	0.065	0.032	0.030	0.58
5	0.51	0.183	0.065	0.046	0.58
6	0.55	0.196	0.036	0.036	0.85
7	0.59	1.16	0.024	0.025	0.48

It will be noted that steel 7 has a very high percentage of silicon ; only one test was made on this steel, but it has been included as being the highest carbon steel tested.

The steels were given various heat treatments, but unfortunately it was impossible to give them all the same heat treatments in order to get complete comparison. In the heat treatments the pieces were kept for ten minutes at the temperatures named.

Table II. gives the heat treatments and the other particulars of the steels. The elongation and the reduction of area were not measured.

TABLE II.

Steel.	Original Diameter. Inches.	Heat Treatment.	Yield Point. Lbs. per Sq. In.	Maximum Stress. Lbs. per Sq. In.
1A	0.5657	920/air.	37,160	59,340
1B	0.5656	920/muffle.	38,565	56,029
1C	0.5651	920/water, 670/water.	47,625	68,575
1D	0.5660	1050/air.	38,235	57,610
1E	0.5657	920/water.	54,765	76,770
1F	0.5650	920/oil.	54,700	73,350
2A	0.5657	880/air.	54,350	77,825
2B	0.5650	880/muffle.	49,855	76,520
2C	0.5657	880/water, 650/water.	68,690	94,930
3A	0.5653	880/air.	52,055	81,460
3B	0.5647	880/muffle.	47,785	76,340
3C	0.5643	880/water, 650/water.	67,795	96,420
3D	0.5647	880/oil.	64,550	96,365
3E	0.5646	880/water, 300/water.	...	110,560
4A	0.5653	850/air.	52,415	90,545
4B	0.5660	850/muffle.	48,865	86,740
4C	0.5653	850/water, 650/water.	69,925	107,845
4D	0.5655	800/air.	55,045	89,505
4E	0.5650	900/air.	51,910	92,675
4F	0.5660	960/air.	49,060	93,540
4G	0.5656	1000/air.	51,625	94,070
4H	0.5655	840/oil.	...	122,630
4I	0.5656	850/water, 580/water.	...	122,885
4J	0.5650	850/water, 440/water.	...	139,920
4K	0.5655	970/water, 580/water.	...	121,835
5A	0.5656	850/air.	56,280	92,935
5C	0.5650	850/water, 650/water.	82,195	116,285
6A	0.5655	850/air.	63,125	106,065
6B	0.5658	850/muffle.	56,795	100,130
6C	0.5658	850/water, 650/water.	87,895	123,810
7A	0.5657	820/air.	76,985	137,385

The steels dealt with have yield points ranging from 16.59 tons per square inch for 1A to 39.24 tons per square inch for 6C (probably higher if the yield points of 4H, 4I, 4J, and 4K could have been read), and maximum stresses ranging from 25.01 tons per square inch for 1B to 62.47 tons per square inch for 4J.

Most of the steels were treated in the form of $1\frac{1}{8}$ inch rounds.

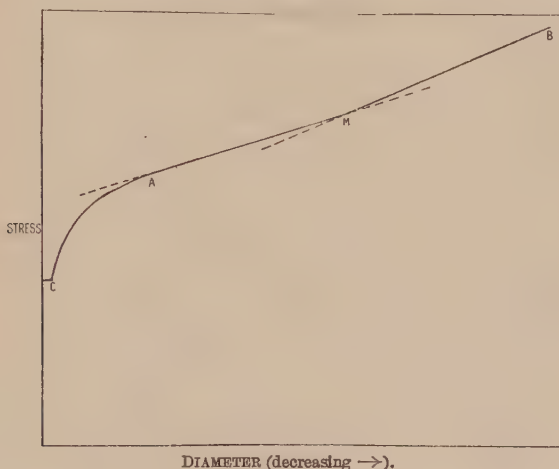


FIG. 3.

No. 7, however, was treated in $1\frac{1}{4}$ inch square, and No. 1 in $1\frac{1}{4}$ inch square cut from a 4-inch square billet.

THE EQUATIONS OBTAINED.

All the steels gave equations of the form $P = a - bd - e^{cd-f}$. There was, however, a slight variation in the case of some of the hardened and tempered steels, in which there is a change of direction in the end part of the curve, about midway between the maximum load and fracture. The type of curve is given in Fig. 3.

The change of direction is not abrupt at M, but there is a slight curvature at that point connecting the two parts of the curve. The portion of the curve MB can be

represented by an equation similar to that which represents AM, viz. $P = a' - b'd$.

The equations obtained for the steels are shown in Table III. Where there is a point of inflexion in the last part of the curve, the equation is put in the last column.

All the constants are calculated in lbs. per square inch.

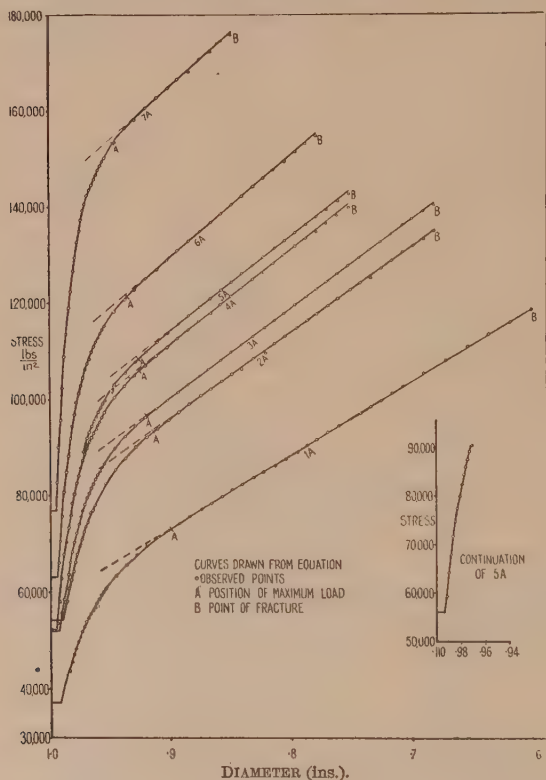


FIG. 4.

A set of curves for the normalised steels 1A, 2A, 3A, 4A, 5A, 6A, and 7A is given in Figs. 4 and 5. Fig. 4 shows the stress-diameter curves, and Fig. 5 the corresponding stress-strain curves.

A set of curves for the hardened and tempered steels 1C, 2C, 3C, 4C, 5C, and 6C is given in Fig. 6, showing the change of direction in the last part of the curve.

TABLE III.

Steel.	Equation.	
1A	$208945-150476d-e^{42 \cdot 3336d-31 \cdot 9760}$	
1B	$201065-145925d-e^{46 \cdot 3634d-35 \cdot 8535}$	
1C	$228930-160488d-e^{55 \cdot 5609d-45 \cdot 1827}$	248835-188743 <i>d</i>
1D	$201300-144330d-e^{46 \cdot 1355d-35 \cdot 7245}$	
1E	$241670-164053d-e^{65 \cdot 2589d-54 \cdot 7637}$	257020-184418 <i>d</i>
1F	$241315-167085d-e^{60 \cdot 6248d-50 \cdot 1989}$	256060-187580 <i>d</i>
2A	$254705-175933d-e^{49 \cdot 8885d-39 \cdot 1727}$	
2B	$252400-175150d-e^{50 \cdot 0870d-39 \cdot 4896}$	
2C	$285980-188944d-e^{64 \cdot 8681d-54 \cdot 1260}$	302460-211005 <i>d</i>
3A	$266810-184854d-e^{58 \cdot 1838d-47 \cdot 3872}$	
3B	$250945-173928d-e^{50 \cdot 6456d-39 \cdot 9403}$	
3C	$291600-192991d-e^{68 \cdot 8655d-58 \cdot 1599}$	303240-2082270 <i>d</i>
3D	$296800-198774d-e^{66 \cdot 4438d-55 \cdot 6337}$	
3E	$315065-200998d-e^{64 \cdot 3520d-53 \cdot 5662}$	
4A	$288380-196744d-e^{62 \cdot 2840d-51 \cdot 4073}$	
4B	$278790-191308d-e^{61 \cdot 6444d-50 \cdot 7504}$	
4C	$315515-204639d-e^{68 \cdot 7271d-57 \cdot 8637}$	328740-221598 <i>d</i>
4D	$286155-195663d-e^{60 \cdot 8061d-49 \cdot 9242}$	
4E	$289465-195490d-e^{68 \cdot 8208d-57 \cdot 8858}$	
4F	$287610-192440d-e^{70 \cdot 5065d-59 \cdot 4873}$	
4G	$289015-193435d-e^{71 \cdot 8892d-60 \cdot 8822}$	
4H	$330815-203580d-e^{74 \cdot 7412d-63 \cdot 6596}$	
4I	$325175-197960d-e^{82 \cdot 8290d-71 \cdot 7953}$	337240-212666 <i>d</i>
4J	$328320-181365d-e^{84 \cdot 8225d-73 \cdot 7811}$	
4K	$315690-189443d-e^{87 \cdot 1114d-76 \cdot 0461}$	
5A	$290295-195698d-e^{61 \cdot 4705d-50 \cdot 4871}$	
5C	$320195-201140d-e^{92 \cdot 3682d-81 \cdot 2398}$	327165-209615 <i>d</i>
6A	$320250-212063d-e^{72 \cdot 1370d-61 \cdot 0088}$	
6B	$309110-207083d-e^{65 \cdot 5310d-54 \cdot 4649}$	
6C	$332330-204820d-e^{91 \cdot 4568d-80 \cdot 3314}$	348045-224623 <i>d</i>
7A	$365480-222886d-e^{80 \cdot 4991d-69 \cdot 0562}$	

As it is impossible to indicate, on such a small scale, the closeness with which the observed points lie on the calculated curve, the actual readings for steel 3A are given in Table IV. (p. 388).

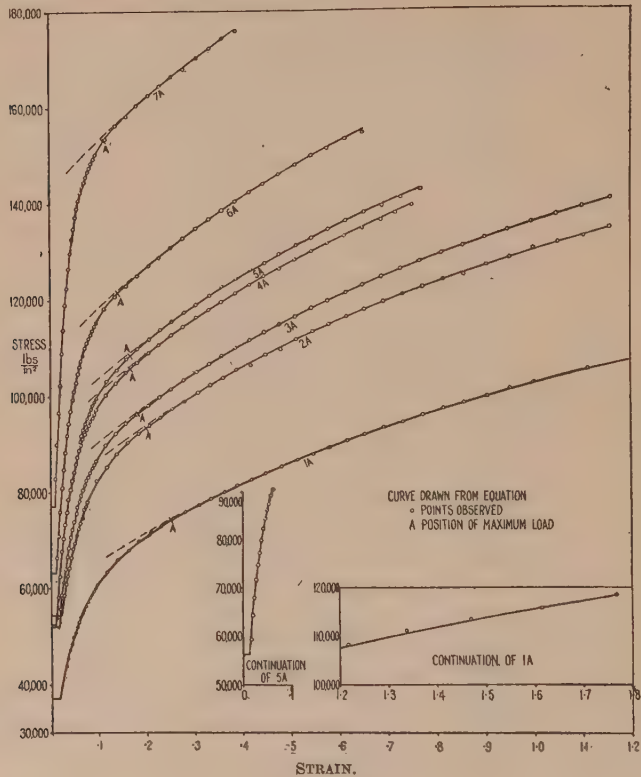


FIG. 5.

The table compares the observed stress with the stress calculated from the equation.

The stresses in all cases are calculated to the nearest 5 lbs. per square inch.

Some of the curves agreed better than the calculated values in the table, and some not so well, but for all the steels the percentage difference between the observed and the calculated values is about 0.1.

Near the yield point and the point of fracture—that is to say, at the two ends of the curve—there is often a considerable difference, but usually only for two or three readings.

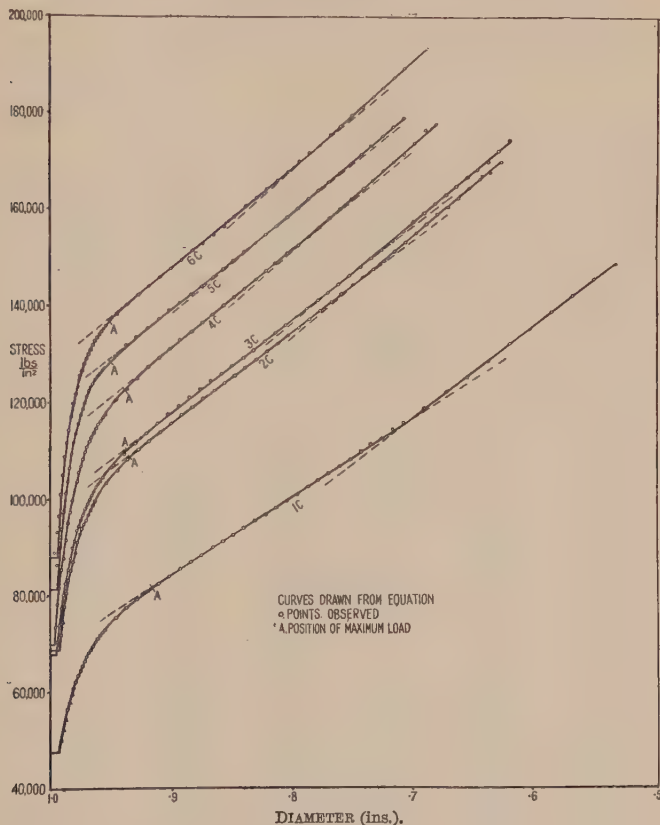


FIG. 6.

INTERPRETATION OF THE EQUATION.

It will be seen at once that the constant a represents the stress the steel would sustain if the diameter were reduced to zero, and though it is impossible to attain this condition, a might be taken as a measure of the strength of the steel.

With regard to the other constants, their meaning will prob-

ably become clearer if the form of the equation be altered somewhat.

TABLE IV.—*Steel 3A. Original Diameter, 0·5653 inch.*

Equation to the curve :

$$266810 - 184854d - e^{58 \cdot 1838d - 47 \cdot 3872}$$

I.	II.	III.	IV.	V.	VI.	VII.	VIII.
0·5653	0	1·000	0·0000	0	0	0	0·0
0·560	13725	0·9906	0·0190	55725	55375	+350	0·63
0·559	14350	0·9889	0·0236	58470	58470	0	0·0
0·558	14940	0·9871	0·0263	61090	61295	-205	0·37
0·557	15575	0·9853	0·0301	63920	63875	+45	0·07
0·556	16115	0·9836	0·0338	66370	66235	+135	0·20
0·555	16550	0·9818	0·0375	68410	68400	+10	0·01
0·554	16995	0·9800	0·0412	70505	70380	+125	0·18
0·553	17335	0·9782	0·0451	72175	72200	-25	0·03
0·552	17665	0·9765	0·0488	73815	73875	-60	0·08
0·551	18000	0·9747	0·0526	75490	75420	+70	0·09
0·550	18300	0·9729	0·0565	77025	76845	+180	0·23
0·549	18490	0·9712	0·0603	78110	78160	-50	0·06
0·548	18760	0·9694	0·0641	79540	79380	+160	0·20
0·547	18925	0·9676	0·0680	80530	80510	+20	0·03
0·546	19100	0·9659	0·0719	81575	81565	+10	0·01
0·545	19300	0·9641	0·0759	82730	82545	+185	0·22
0·544	19410	0·9623	0·0798	83510	83465	+45	0·05
0·543	19520	0·9606	0·0838	84295	84325	-30	0·04
0·542	19625	0·9588	0·0878	85060	85135	-75	0·09
0·541	19725	0·9570	0·0918	85810	85895	-85	0·10
0·540	19830	0·9552	0·0959	86585	86615	-30	0·03
0·535	20205	0·9464	0·1165	89880	89705	+175	0·19
0·530	20350	0·9376	0·1377	92240	92210	+30	0·03
0·525	20445	0·9287	0·1594	94445	94365	+80	0·08
0·520	20445	0·9199	0·1818	96270	96300	-30	0·03
0·515	20420	0·9110	0·2049	98025	98125	-100	0·10
0·510	20370	0·9022	0·2286	99715	99870	-155	0·15
0·505	20320	0·8933	0·2531	101455	101575	-120	0·12
0·500	20260	0·8845	0·2782	103185	103250	-65	0·06
0·495	20185	0·8756	0·3045	104890	104910	-20	0·02
0·490	20095	0·8668	0·3311	106565	106560	+5	0·00
0·485	20005	0·8580	0·3585	108280	108200	+80	0·08
0·480	19900	0·8491	0·3869	109970	109840	+130	0·12
0·475	19765	0·8403	0·4163	111535	111480	+55	0·05
0·470	19630	0·8314	0·4467	113150	113115	+35	0·03
0·465	19485	0·8226	0·4779	114740	114755	-15	0·01
0·460	19340	0·8137	0·5102	116375	116390	-15	0·01
0·455	19175	0·8049	0·5434	117925	118025	-100	0·09
0·450	19040	0·7960	0·5780	119720	119660	+60	0·05
0·445	18865	0·7872	0·6136	121295	121295	0	0·00
0·440	18690	0·7784	0·6508	122920	122930	-10	0·01
0·435	18510	0·7695	0·6888	124550	124565	-15	0·01
0·430	18325	0·7607	0·7285	126190	126200	-10	0·01
0·425	18140	0·7518	0·7692	127875	127835	+40	0·03
0·420	17935	0·7430	0·8115	129455	129470	-15	0·01

TABLE IV.—*Continued.*

I.	II.	III.	IV.	V.	VI.	VII.	VIII.
0.415	17740	0.7341	0.8554	131145	131105	+40	0.03
0.410	17530	0.7253	0.9013	132775	132740	+35	0.03
0.405	17310	0.7164	0.9482	134365	134375	-10	0.01
0.400	17105	0.7076	0.9973	136120	136010	+110	0.08
0.395	16860	0.6988	1.0482	137590	137645	-55	0.04
0.390	16625	0.6899	1.1010	139170	139280	-110	0.08
0.385	16350	0.6811	1.1599	140440	140915	-475	0.34
Average difference						79	0.09

Column I. gives the diameter as measured, column II. the load, column III. the diameter reduced for an original diameter of 1, column IV. the strain, column V. the stress calculated from the first two columns, column VI. the stress as calculated from the equation, column VII. the difference between columns V. and VI., and column VIII. the percentage difference.

Putting $d = 1$ in equation (2), the value of the stress where the curve cuts the stress axis is obtained. Call this P_o .

Then

$$P_o = a - b - e^{c-f}, \text{ giving } a = P_o + b + e^{c-f}.$$

Hence the equation may be written :

$$P = P_o + b(1 - d) + e^{c-f} \{ 1 - e^{-c(1-d)} \} \quad . \quad . \quad (4)$$

$1 - d$ is the decrease in diameter; calling this y for simplicity the equation becomes :

$$P = P_o + by + e^{(c-f)}(1 - e^{-cy}) \quad . \quad . \quad (5)$$

P_o is a constant that depends only on the nature of the steel and not at all on the cold-working. Its meaning will be discussed later. The other two terms represent the increase in the stress that the steel can support, which is brought about by hardening, due to cold-working. Since they are quite distinct in form, they indicate that two distinct processes take place during cold-working.

Hardening by cold-working is due to slip. This slip can take place either in the crystallites along the slip planes, or between the crystallites themselves. The two terms in the equation (5) must therefore refer to these two different types of slip, which for simplicity will be called internal and external slip respectively.

The next question is, Which term refers to a particular type of slip? Since both slips must take place together, it is impossible to devise an experiment by which each type could be examined alone.

From microscopic examination it is known that the first slip that takes place is chiefly internal, and, further, that after a definite amount of cold-working internal slip practically ceases, and on further cold-working slip is wholly external. This points directly to the term $e^{c-f}(1 - e^{-cy})$, as referring to the internal slip, since its value tends to one which can never be exceeded, and also its increase is greatest at the beginning of cold-working; while the term by increases steadily and has not a value which it cannot exceed.

Again, in any given steel the slip is partly internal and partly external for any given elongation. If the size of the crystallites be increased, the effect should be to change the ratio of internal to external slip taking place for the same elongation. Exactly how the ratio will be changed it is difficult to say; but since the area over which internal slip can take place would be increased, and the corresponding external area decreased, by increasing the size of the crystallites the internal slip should be increased and the external decreased, and the hardening due to each slip should alter in the same way. This was tested by comparing the equations for steels differing only in the size of the crystallites.

TABLE V.

Steel.	b .	c .
4A	196744	62.2840
4E	195490	68.8208
4F	192440	70.5065
4G	193435	71.8892
1A	150476	42.3336
1D	144330	46.1355
4I	197960	82.8290
4K	189443	87.1114

Steels 4A, 4E, 4F, and 4G were heated to 850°, 900°, 960°, and 1000° respectively and cooled in air, thus producing different

sized crystallites. Similarly, steels 1A and 1D were heated to 920° and 1020° respectively; and steels 4I and 4K were heated to 850° and 970°, quenched in water, and then both tempered at 580°. In Table V. are given the values of b and c for the steels.

It will be seen that in all cases the value of c increases with the temperature—that is, with the crystallite size; and the value of b decreases, except in the case of 4G, where its value is greater than that in 4F. These figures may be taken as proving that the term $e^{c-f}(1 - e^{-c})$ refers to the internal, and the term by to the external slip.

GENERAL CONSIDERATION OF THE CONSTANTS.

The data are quite insufficient to deduce any connection between the value of the constants and the heat treatment of the steels, but one or two general inferences may be made.

If all the steels are considered, there is no one property of the steel with which the constants can be compared, except perhaps the hardness. No measurements were made of the hardness, so that the maximum stress is taken instead. In Table VI. is given a comparison of the maximum stress and the constants.

TABLE VI.

Steel.	Maximum Stress.	a .	b .	c .
1A	59342	208945	150476	42.3336
1B	56029	201065	145925	46.3634
1C	68577	228930	160488	55.5609
1D	67610	201300	144330	46.1355
1E	76768	241670	164053	65.2589
1F	73349	241315	167805	60.6248
2A	77823	254705	175933	42.8885
2B	76520	252400	175150	50.0870
2C	94930	285980	188944	64.8618
3A	81460	266810	184854	58.1838
3B	76340	250945	173928	50.6456
3C	96420	291600	192991	68.8655
3D	96365	296800	198774	66.4438
3E	110560	315065	200998	64.3520

TABLE VI.—*Continued.*

Steel.	Maximum Stress.	<i>a.</i>	<i>b.</i>	<i>c.</i>
4A	90545	288380	196744	62·2840
4B	86740	278790	191308	61·6464
4C	107845	315515	204639	68·7271
4D	89505	286155	195663	60·8061
4E	92675	289465	195490	68·8208
4F	93540	287610	192440	70·5065
4G	94070	289015	193435	71·8892
4H	122630	330815	203580	74·7412
4I	122885	325175	197960	82·8290
4J	139920	328320	181365	84·8225
4K	121835	315690	189443	87·1114
5A	92935	290295	195698	61·4705
5C	116285	320195	201140	92·3682
6A	106067	320350	212063	72·1370
6B	100128	309110	207083	65·5310
6C	123812	332330	204820	91·4568
7A	137385	365480	222886	80·4991

It will be seen that, in general, *a* increases with the maximum stress and so does *c*, though there is no definite relation in either case.

There is no connection whatever between *b* and the maximum stress.

It will also be seen that for any one steel neither *a* nor *b* varies greatly in value compared with the variations of the maximum stress, while *c* varies very greatly. In Table VII. are given the percentage variations between the least and greatest values of the maximum stress, *a*, *b*, and *c*.

TABLE VII.

Steel.	Maximum Stress.	<i>a.</i>	<i>b.</i>	<i>c.</i>
1	37·08	19·87	16·28	54·15
2	24·06	13·30	7·90	30·03
3	44·86	21·56	15·52	35·98
4	61·84	18·66	12·84	43·00
5	25·13	10·30	2·76	51·88
6	23·65	7·51	3·54	36·50

Thus it appears that the effect of different heat treatments on the steels is to modify the internal slip very considerably, while not affecting the external slip to any great extent.

The effect of grain size has already been discussed. The only other variation for which there is any data is the effect of altering the tempering temperature.

Steels 4C, 4I, and 4J were all quenched at 850°, and tempered at 650°, 580°, and 440° respectively. In Table VIII. are given the values of b and c .

TABLE VIII.

Steel.	b .	c .
4C	204639	68·7271
4I	197960	82·8290
4J	181365	84·8225

Thus the effect of raising the temperature is to increase b and to decrease c .

The only other general relationship that can be found is between the carbon content and the constants for similarly treated steels. If, for normalised steels, the values of a , b , and c are plotted against the carbon content, the points in each case will be found to lie practically on a straight line. This is shown in Table IX. and Fig. 7. Steel 7 is omitted owing to its high percentage of silicon.

TABLE IX.

Steel.	Carbon.	a .	b .	c .
1A	0·16	208945	150476	42·3336
2A	0·28	254705	175933	49·8885
3A	0·34	266810	184854	58·1838
4A	0·44	288380	196744	62·2840
5A	0·51	290295	195698	61·4705
6A	0·55	320350	212063	72·1370

The approximation to a straight line is rough, but gives some indication of the increase of the various constants with the carbon content.

The equations to the lines are :

$$a = 175190 + 261700 C; \quad b = 139250 + 132000 C; \quad c = 30 \cdot 0484 + 76 \cdot 0352 C,$$

which give values for pure iron of :

$$a = 175190; \quad b = 139250; \quad c = 30 \cdot 0484,$$

and an increase for each 0.01 per cent. of carbon of 1.5 per cent.

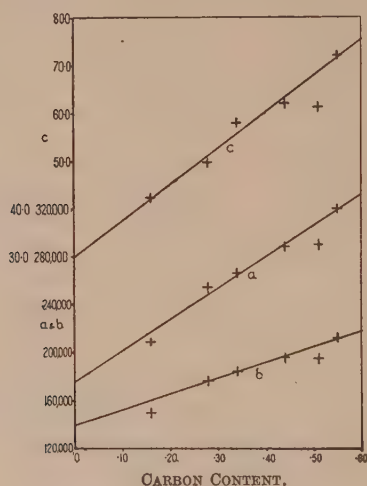


FIG. 7.

for a , 1 per cent. for b , and 2.9 per cent. for c , showing again that it is the internal slip that varies the most.

THE MAXIMUM HARDENING AND THE YIELD-POINT SLIP.

Considering the equation in the form :

$$P = P_0 + b(1 - d) + e^{c-f} \{ 1 - e^{-c(1-d)} \}$$

the maximum possible hardening is given by e^{c-f} for the internal slip, and by b for the external slip. This maximum can only occur when all the slip produces hardening, that is, when there is no yield-point slip. The values of $c-f$ for all the steels are given in Table X.

TABLE X.

Steel.	$c - f$.	Steel.	$c - f$.	Steel.	$c - f$.
1A	10·3576	3A	10·7966	4J	11·0414
1B	10·5099	3B	10·7053	4K	11·0653
1C	10·3782	3C	10·7056	Mean	10·9729
1D	10·4110	3D	10·8101		
1E	10·4952	3E	10·7858	5A	10·9834
1F	10·4259	Mean	10·7607	5C	11·1384
Mean	10·4298			Mean	11·0608
2A	10·7158	4A	10·8767	6A	11·1282
2B	10·5974	4B	10·8940		
2C	10·7421	4C	10·8634	6B	11·0661
Mean	10·6851	4D	10·8845	6C	11·1254
		4E	10·9350	Mean	11·1068
		4F	11·0192		
		4G	11·0070	7A	11·4428
		4H	11·0816		
		4I	11·0338		

It will be seen that the variation is not great between 10·3576 and 11·4428; and for any one steel the value remains nearly constant whatever the heat treatment. The mean values for each steel are given in the table. The maximum variation from the mean in each case is about 2 per cent., though the variation for c , as has been seen, may be as much as 50 per cent.

If the mean values are plotted against the carbon content, the points lie practically on a straight line.

This is shown in Fig. 8 (Steel 7 is omitted). The equation to the line is:

$$c - f = 10·1724 + 1·7466 C.$$

This represents an increase on the value 10·1724 for pure iron of 0·2 per cent. for each 0·01 per cent. increase in C .

The maximum hardening for internal and external slip differs very greatly. The following are the highest and lowest values for the two slips:

	$c - f$.	b .
Lowest . . .	31496	144330
Highest . . .	93240	222886

so that the external is always much greater than the internal. It must be remembered, however, that all the internal harden-

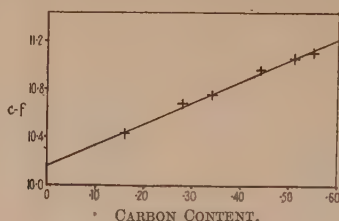


FIG. 8.

ing has taken place before fracture, while at most only about 50 per cent. of the external, and the full value of the latter



FIG. 9.

cannot be obtained without pulling the piece until the diameter is zero.

The maximum hardening is never obtained, even for internal slip, in any steel which shows a yield-point slip. In any steel in which maximum hardening was obtained the curve would be continuous, and would show no horizontal portion at the yield point. This can be seen from Fig. 9. ABCE is the ordinary stress-diameter curve. CD is obtained by producing the curve $P = P_o + (1 - d) b + e^{c-f} (1 - e^{-c(1-d)})$ backwards, so that $AD = P_o$. If there were no yield-point slip the curve would be of the form ABE", obtained by moving the whole of the portion DCE vertically through a distance BD until D coincides with B. The equation would become :

$$P = P_1 + (1 - d) b + e^{c-f} \{ 1 - e^{-c(1-d)} \}$$

where $P_1 = AB =$ yield stress.

The actual hardening, therefore, is less than the maximum hardening by an amount $P_1 - P_o$. This is the hardening produced by the slip represented by BC, that is, the yield-point slip ; so that the yield-point slip does not produce any hardening.

The lost hardening is chiefly in the internal slip. In the following table are shown the limits between which the lost hardening varies for the steels which show a definite yield point ; the limits of the lost internal and external hardening are also given :

Total.	Internal.	External.
31220	29955	1845
11275	10225	675

Thus it will be seen that the external is nearly negligible compared with the internal. Also there is no relation between the two.

For the internal hardening the percentage of lost hardening to maximum hardening varies between 20 per cent. and 40 per cent.

The values of the lost hardening depend entirely on the extent of the yield-point slip, and as far as these experiments go this is quite indeterminate.

In Table XI. are given the limits within which the yield-point slip varies for all the steels, given as the decrease in diameter that takes place at the yield.

TABLE XI.

Steel:	1.	2.	3.	4.	5.	6.	7.
Highest .	0·01456	0·01078	0·00748	0·00500	0·00646	0·00558	0·00419
Lowest .	0·00634	0·00673	0·00493	0·00330	0·00628	0·00494	...

Except that the yield-point slip decreases as the hardness of the steel increases, there seems to be no connection between it and any of the constants of the steel.

Similarly, the value of P_0 is also an independent variable and has no relation to the yield stress, as Table XII. shows.

TABLE XII.

Steel.	Yield Point.	P_0 .	Steel.	Yield Point.	P_0 .
1A	37160	26971	4A	52415	38728
1B	38565	18466	4B	48865	33628
1C	47625	36291	4C	69925	58648
1D	38235	23750	4D	55045	37152
1E	54765	46342	4E	51910	37870
1F	54700	40789	4F	49060	34132
			4G	51025	35282
2A	54350	33711			
2B	49855	37219	5A	56280	35710
2C	68690	50765	5C	82195	50978
3A	52055	33102	6A	63125	40226
3B	47785	32431	6B	56795	38068
3C	67795	54003	6C	87895	59637
3D	64550	48503			
			7A	76985	49355

Nor has it any relation to any of the other constants of the steel. It might depend on the true elastic limit of the steel, but as this was not determined for any of the steels, nothing definite can be said on this point. The values of P_0 seem too low for it to represent the actual elastic limit.

THE MAXIMUM LOAD.

The maximum load can be obtained from the equation as follows :

Load at any diameter, d :

$$W = \frac{\pi d^2}{4} P = \frac{\pi d^2}{4} (a - bd - e^{cd} - f) \quad . \quad . \quad . \quad (6)$$

The maximum load is found by differentiating this with regard to d , and equating to zero.

This gives

$$2a - 3bd - (cd + 2)e^{cd} - f = 0.$$

Putting $y = cd - f$, the equation becomes

$$(y + f + 2) e^y + \frac{3b}{c}y - \left(2a - \frac{3bf}{c}\right) = 0 \quad . \quad . \quad . \quad (7)$$

There is no general solution for this, and it can only be solved by trial. Having obtained the value of y by trial, d can be obtained and the maximum load obtained, substituted in the equation (6). The maximum stress $\frac{\text{maximum load}}{\text{original area}}$ can then be obtained.

$$\text{Maximum load : } W = \frac{\pi d^2}{4} (a - bd - e^{cd} - f).$$

$$\text{Original area} = \frac{\pi D^2}{4}$$

$$\text{Maximum stress} = \frac{d^2}{D^2} (a - bd - e^{cd} - f).$$

If, as in the case of all these equations, $D = 1$,

$$\text{Maximum stress} = d^2 (a - bd - e^{cd} - f).$$

Since there is no general solution for equation (7), no relation can be found between the constants and the maximum stress.

If, however, the position of the maximum load on the curves is examined, it is found to be at a point where the hardening due to internal slip has nearly come to an end (Figs. 4, 5, and 6).

In Table XIII. is given the total hardening, the internal hardening, and the external hardening; between the yield point and the maximum load; and also the value of the term

e^{cd-f} at the maximum load ; this last representing the amount of internal hardening still to take place.

TABLE XIII.

Steel.	Hardening.			e^{cd-f} at Maximum Load.
	Internal.	External.	Total.	
1A	22150	14664	36724	356
1B	18438	13486	31924	258
1C	21611	12275	33886	313
1D	19966	13376	33342	310
1E	23486	10260	33746	404
1F	19919	11560	31479	304
2A	25737	13445	39182	582
2B	27970	13485	41455	604
2C	28969	11032	40001	672
3A	31273	13636	44909	434
3B	29972	13732	43704	560
3C	31163	11098	42261	581
3D	33973	12224	46197	606
3E	...	...	...	415
				Yield point not obtained.
4A	39602	13775	53377	512
4B	39094	14136	53230	474
4C	40815	11711	52526	815
4D	36128	13708	49836	519
4E	42330	12670	55000	495
4F	46298	12180	58478	540
4G	44804	11596	56400	522
4H	...	...	...	1151
4I	...	...	...	1060
4J	...	...	...	1635
4K	...	...	...	1057
				Yield point not obtained.
5A	38959	13201	52160	626
5C	37382	8584	45966	740
6A	45641	12522	58163	654
6B	45613	13506	59119	645
6C	39868	8564	48432	890
7A	65172	10749	75921	1371

It will be seen that in all cases the internal hardening is greater than the external, varying from 1.5 to 6 times as great. For any one steel the total hardening does not vary greatly, on an average about 10 per cent. only.

The values in the last column are very small, except in the case of the hardest steels. For the rest the mean value is 565.

It follows, therefore, that the maximum load occurs at a point where the internal hardening has reached to within 565 lbs. per square inch of its maximum value.

The stress at the maximum load is therefore given by the equation:

$$P = a - bd - 565,$$

and since

$$\begin{aligned} e^{cd} - f &= 565 \\ cd - f &= 6 \cdot 3368 \end{aligned}$$

and

$$d = \frac{f + 6 \cdot 3368}{c}$$

so that the maximum stress

$$= \left(\frac{f + 6 \cdot 3368}{c} \right)^2 \left\{ a - b \left(\frac{f + 6 \cdot 3368}{c} \right) - 565 \right\} . \quad . \quad . \quad (8)$$

Thus, though it is impossible to get an exact equation between the maximum stress and the constants, an empirical relation can be obtained which gives the value of the maximum stress with considerable accuracy, as will be seen in Table XIV., in which the calculated and observed values are given together with the difference and the percentage error.

It will be seen that the calculated value differs from the observed, on an average by about 0·1 per cent.

From the value

$$d = \frac{f + 6 \cdot 3368}{c}$$

it follows that the diameter at the maximum load depends only on the internal hardening and not at all on the external, which is more or less to be expected, as the maximum load occurs where the internal slip has practically ceased. It follows also that the diameter is by no means constant. The value of $c - f$ is nearly constant; hence the larger the value of c the smaller is the value of the diameter.

In Table XV. are given the limits between which the diameter at the maximum load varies for each steel. This is calculated from equation (7) and not from equation (8).

TABLE XIV.

Steel.	Maximum Stress.		Difference.	Error per Cent.
	Observed.	Calculated.		
1A	59342	59131	-211	0·343
1B	56029	56061	+32	0·057
1C	68577	68397	-180	0·264
1D	57610	57477	-133	0·231
1E	76768	76708	-60	0·078
1F	73348	73279	-170	0·232
2A	77823	77931	+108	0·139
2B	76520	76697	+177	0·231
2C	94951	94960	+9	0·009
3A	81473	81460	-13	0·016
3B	76340	76357	+17	0·022
3C	96420	96739	+319	0·336
3D	96365	96420	+55	0·058
3E	110560	110136	-424	0·395
4A	90545	90604	+59	0·065
4B	86740	86668	-72	0·083
4C	107845	108020	+175	0·162
4D	89505	89506	+1	0·001
4E	92675	92719	+44	0·048
4F	93540	93596	+56	0·060
4G	94070	94057	-13	0·014
4H	122630	122433	-197	0·161
4I	122885	122683	-202	0·165
4J	139920	139576	-344	0·246
4K	121835	121605	-230	0·189
5A	92935	92994	+59	0·064
5C	116285	115895	-390	0·336
6A	106067	106163	+96	0·090
6B	100128	100211	+83	0·083
6C	123812	123630	-182	0·147
7A	137385	136996	-389	0·288

TABLE XV.

Steel.	1.	2.	3.	4.	5.	6.	7.
Highest	0·93112	0·93477	0·93995	0·95706	0·95105	0·95261	0·94758
Lowest	0·89305	0·91279	0·91885	0·92323	0·92608	0·92984	...

THE BREAKING STRESS.

In these experiments the breaking stress could not be obtained, since the diameters were only measured at definite intervals, and the piece invariably broke between two readings. Thus only the limits between which it must lie could be obtained. It is useless to calculate the stress from the diameter measured after fracture, since there is always a very considerable contraction during or after actual fracture.

The only relationship which seemed to hold between the breaking stress and anything else was that it varied linearly with the yield stress, but since no actual readings were taken nothing further need be said.

FURTHER EXPERIMENTS.

Experiments were made to see whether the dimensions of the test-piece had any effect on the equation obtained.

Steel similarly treated to 3A was used, and nine pieces having the following dimensions were pulled :

Steel.	Length between Shoulders.	Diameter.
	Inches.	Inch.
3A1	2·6	0·6402
3A2	2·6	0·5200
3A3	2·6	0·4001
3A4	5·6	0·6402
3A5	5·6	0·5202
3A6	5·6	0·4002
3A7	7·7	0·6399
3A8	7·7	0·5200
3A9	7·7	0·4005

They gave the following equations (Table XVI.). The equation was calculated for an original diameter of one in each case. The yield point and maximum stress is also given for comparison.

The difference between the highest and lowest values is calculated, and its percentage on the mean value is taken as the variation.

TABLE XVI.

Steel.	<i>a.</i>	<i>b.</i>	<i>c.</i>	<i>c - f.</i>	Yield Point.	Maximum Stress.
3A1	269450	186940	56·3113	10·7737	49875	81840
3A2	268495	187200	56·4199	10·7700	51845	81210
3A3	268605	187200	57·2883	10·7754	52095	81250
3A4	268780	188200	56·3111	10·7774	51800	80585
3A5	267720	187270	56·5363	10·7425	51875	80435
3A6	268560	189290	55·2897	10·7956	50560	79300
3A7	267340	189410	56·3111	10·7280	49505	78345
3A8	270650	192400	56·5363	10·7241	51300	78990
3A9	270360	190540	55·7640	10·7413	49425	79975
Mean .	268885	188820	56·3076	10·7588	50920	80215
Variation per cent. .	1·23	2·9	3·55	0·66	5·24	4·35

It will be seen that the variation in the constants is very small, and is always smaller than the variation in the yield point and the maximum stress.

When plotted, the curves for pieces of similar length most nearly coincide. Taking the mean values for the pieces of similar length, the values shown in Table XVII. are obtained.

TABLE XVII.

Length.	<i>a.</i>	<i>b.</i>	<i>c.</i>	<i>c - f.</i>
Feet.				
2·6	268850	187113	56·6732	10·7730
5·6	268353	188260	56·0457	10·7719
7·7	269450	190783	56·2038	10·7311

Therefore it appears that *b* increases with the length, while *a* and *c* vary irregularly. In all probability all the variations are within the experimental error, and the general conclusion is that the dimensions probably have no effect on the equation, but if they do, it is only the length that has any effect.

THE EFFECT OF COLD-WORK.

One experiment was made on cold-worked steels. Two steels similarly treated to 2A were pulled in the machine to different loads, were then released and allowed to rest. They were then pulled in the ordinary way.

The results obtained were compared with 2A.

The maximum load for 2A was 19,560 lbs. 2A1 was loaded to 16,500 lbs., kept there five minutes, released, and set aside for twenty-two hours. 2A2 was loaded in stages to 19,500 lbs., kept there five minutes, released, and set aside for three hours. The diameters in each case were measured before the pieces were released from the machine and after they had rested; in all cases the diameters were practically constant over the whole length of the piece, varying only by a maximum of 0.0005 inch. Unfortunately, in stressing 2A1 and 2A2 the yield points were not noted, so that no comparison could be made with 2A.

The steels could, however, be compared in a slightly different way, by comparing the loads and stresses at similar diameters.

The following were the respective diameters:

Steel.	Original.	In Machine.	After Rest.
2A	0.5647	...	...
2A1	0.5647	0.5480	0.5537
2A2	0.5647	0.5355	0.5361

If the loads and stresses of 2A and 2A1 at 0.5480, and those of 2A and 2A2 at 0.5355 are compared, it will give some relation between the steels.

The figures are given in Table XVIII.:

TABLE XVIII.

Steel.	Load at 0.5480.	Stress at 0.5480.	Difference.	Load at 0.5355.	Stress at 0.5355.	Difference.
2A	17600	74620	...	19000	84750	...
2A1	16500	69955	-4665	...	...	...
2A2	...	...	...	19500	86615	+1865

The value of the stress for 2A1 is smaller, and that for 2A2 is larger, than the corresponding value for 2A. It follows that if the steels had all been pulled similarly the curve for 2A1 would be below, and that for 2A2 would be above, the curve for 2A. This is accounted for by some slight variation in the steels or in the heat treatment.

The equations to the curves can be calculated in two ways : on the diameter before they were cold-worked, and on the diameter after cold-working.

In Table XIX. are given the constants of the equations obtained when calculated on the original diameter, those of 2A being also given for comparison.

TABLE XIX.

Steel.	<i>a.</i>	<i>b.</i>	<i>c.</i>	<i>c-f.</i>
2A	254705	175933	49·8885	10·7158
2A1	254235	178769	53·5688	10·6734
2A2	254560	174236	...	...

The determination of *c* and *f* in the case of 2A2 was practically impossible, as the curve consisted almost entirely of the last straight part and none of the curved first part.

The curves are plotted in Fig. 10.

From the curves it will be seen that the last parts are practically parallel, 2A2 being above and 2A1 being below 2A, as was anticipated above.

Comparing the stresses at the same diameters on the curves, the following values are obtained :

Steel.	Stress at Diameter, 0·9015.	Difference.
2A2	96925	+ 1225
2A	95700	...
2A1	92520	-3180

The differences are of the same order to those obtained above, and since they were obtained on different parts of the curves, it may be assumed that the differences between the curves is

due to the variation of the steel and not to cold-work, and if the steels had been absolutely identical the curves would have coincided.

In Table XX. are given the constants of the equations calculated on the diameter after cold-working. 2A is included for comparison :

TABLE XX.

Steel.	<i>a.</i>	<i>b.</i>	<i>c.</i>	<i>c - f.</i>
2A	254705	175933	49·8885	10·7158
2A1	254235	174969	52·5046	9·6624
2A2	254560	165119	....	...

The value of *b* decreases with the increase in cold-working, and when plotted gives the curves shown in Fig. 11.

The figure is not to scale, the distance between the curves having been exaggerated, since, plotted to the true scale, the curves would appear so close together as to be indistinguishable, owing to the fact that the amount of cold-work that they have undergone is very small.

The important point is that, if produced, the curves all meet in a point where $d = 0$, the value of *a* being the same in all three cases.

If other steels had been more severely cold-worked it may be assumed that a series of curves would have been obtained as in Fig. 12, which would all meet at a point where $d = 0$, the slope of the curve diminishing with increasing cold-working.

If the amount of cold-work the steels have undergone is measured by the decrease in diameter caused by the cold-work, then the slope of the curve gives the measure of the cold-work they have undergone. If *b* is the value for the external hardening in the unworked steel, and b_1 the value in a worked steel, which has been reduced in diameter from 1 to *D* by cold-work,

then
$$\frac{b}{b_1} = \frac{1}{D}$$

So that if *b* is known for the unworked steel, the amount of the cold-working of any other steel can be calculated its equation.

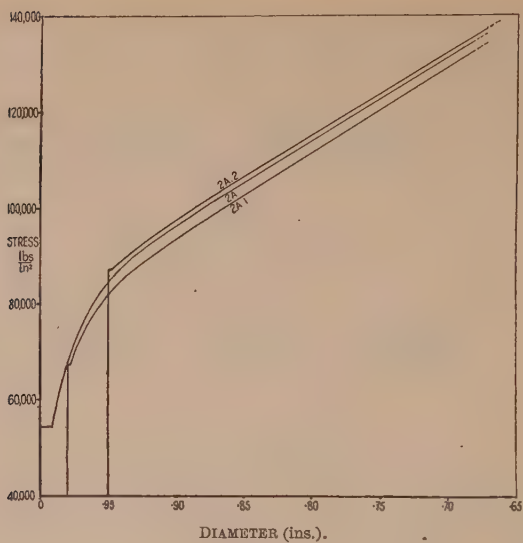


FIG. 10.

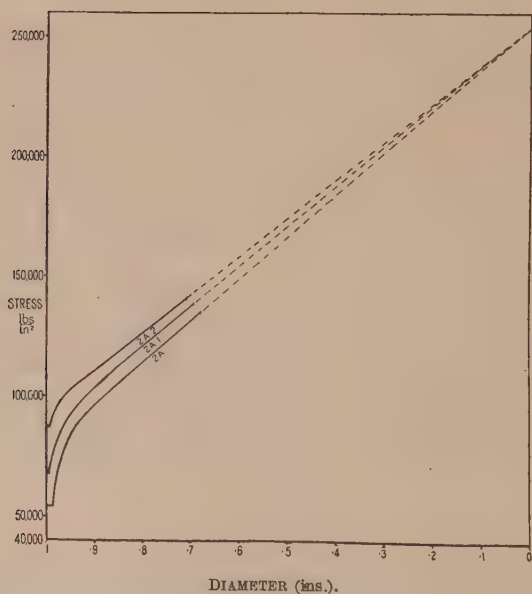


FIG. 11.

CURVE OBTAINED BY DISCONTINUOUS STRESSING.

The process that actually takes place in the tensile test is as follows: When a certain stress is reached slip takes place, bringing about a decrease in diameter and producing hardening, and the steel can now sustain a greater stress without undergoing further slip. When a certain higher stress is reached further slip takes place, accompanied by hardening, and the process is repeated over again. The stress-diameter curves therefore really consist of a series of yield points, represented by a horizontal line, followed by a vertical line representing the increase in stress that the steel can sustain owing to the hardening. (The vertical part is not truly vertical, the slope being Young's modulus of the steel, but for simplicity it can be considered vertical.)

In continuous pulling the horizontal portion is extremely small, depending on the rate of pulling, and in the ordinary test is so small as to be indistinguishable from a smooth curve. A stepped curve was, however, produced as follows:

The piece was pulled until the yield point was reached, which was shown by the jockey becoming stationary. The motor was then immediately stopped. The diameter of the piece was measured, and the jockey run back until balance was again restored, since any elongation of the piece automatically produces a reduction in the load. The motor is then restarted and the jockey moves forward. When it again becomes stationary the motor is again stopped, and the whole process repeated until fracture. Thus the piece is pulled up to successive yield points. Assuming that the slip only takes place at the yield, and not while the piece is being pulled up to the yield, the stress at each successive yield point can be calculated.

In carrying out experiments on these lines the above procedure had to be modified slightly. Between the yield point and the maximum load the slip takes place throughout the whole of the piece, but not simultaneously, starting in one place and then spreading to the whole piece. If the motor be stopped the moment the yield point is reached, owing to the immediate reduction of the load, slip only takes place in a small part of the piece, and in order to get the piece to slip throughout it is

necessary to bring the piece up to the same yield point a great number of times. The time occupied by such a process would have necessitated about forty-eight hours to complete the experiment, and this was not possible.

Up to the maximum load, therefore, the motor was left on after the yield had been reached for varying times, which

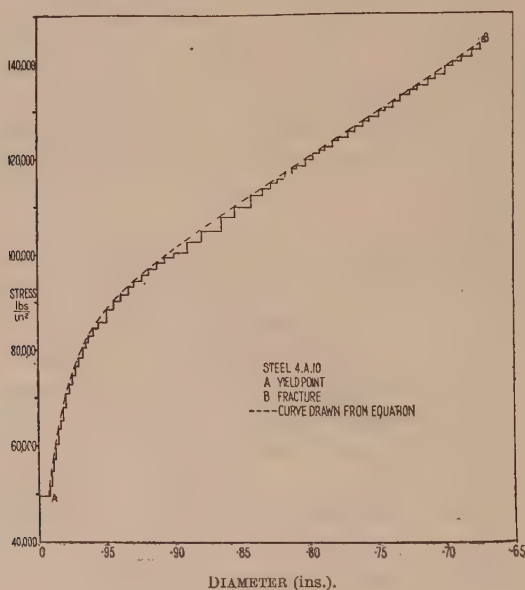


FIG. 12.

gradually diminished as that point was approached. In the neighbourhood of the maximum load, in order to test if any difference was introduced by making the steps larger, the motor was then left on for a considerable time after the yield had been reached, thus increasing the length of the slip. For the end portion of the curve the motor was stopped directly the yield was reached.

Steel 3A10, similarly heat-treated to 3A, was tested in this way, and the curve obtained was identical with those obtained in the ordinary way (Fig. 12).

The equation to this curve is :

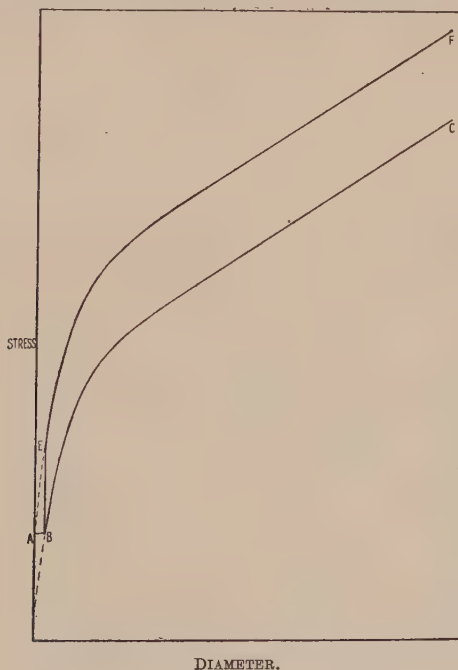
$$P = 269760 - 187281d - e^{53.7738d - 43.0284}$$

compared with

$$P = 269760 - 188820d - e^{56.3076d - 45.5488}$$

the mean equation obtained for 3A steels.

That this method of pulling the piece does not alter the hardening produced is shown by the fact that the hardening



DIAMETER.

FIG. 13.

between the yield point and the maximum load, and the hardening between the yield point and the point of fracture, is the same (allowing for experimental error) in the two cases, thus :

	Hardening.	
	Yield Point to Maximum Load.	Yield Point to Fracture.
3A10 . . .	44195	89615
Mean of 3A . . .	44870	89445—91305 ¹

¹ This figure is given as a limit, as the actual stress at fracture could not be measured.

These results show the process that actually takes place when a piece is pulled, and also that the yield-point slip does not produce any hardening. If it did the curve would rise vertically when the slip had come to an end, until it met the curve representing total possible hardening, as shown in Fig. 13.

The curve would be of the form ABEF instead of ABC; AEF being the curve produced if all slip produced hardening.

Other steels besides those mentioned already were similarly examined, including two nickel-chromium steels. Altogether over sixty equations were obtained in every case of the form $P = a - bd - e^{cd-f}$.

THE PROCESS OF HARDENING BY COLD-WORK.

No attempt can be made to evolve a theory of hardening on the insufficient data given in this paper. However, a few details can be added to the ordinary theory of hardening.

There are three stresses which are characteristic of any steel :

- (1) The stress required to destroy the cohesion between the atoms in the space lattice of the crystals, S_1 . This is constant for any steel but has never been measured, though it is certainly not less than the breaking stress. This might be called the true tensile strength of the steel.
- (2) The stress required to produce internal slip, S_2 . This is characteristic of each steel, but does not remain constant in the same steel, as it depends on the amount of slip that has taken place, increasing with the amount of slip. Its value for the case in which no slip has previously taken place is given by the yield-point stress.
- (3) The stress required to produce external slip, S_3 . This is characteristic of the steel, and like S_2 it varies with the amount of slip that has taken place. Its value is never directly measured, but the initial value is greater than the initial value of S_2 , but is less than the value of S_1 .

Though S_2 and S_3 both vary with the amount of slip that has taken place, the variation is not the same in the two cases.

Taking the decrease in diameter as a measure of the slip, S_2 varies exponentially with the amount of slip, and S_3 linearly.

When internal slip takes place it is always accompanied by some external slip in the form of adjustment; external slip, however, can take place without any internal slip. In any steel the crystallites are in what may be called a state of unstable equilibrium, due to the stresses which exist in every steel.

When a test-piece is stressed the stress rises elastically until the initial value of S_2 is reached, and then internal slip takes place. The crystallites being in a state of unstable equilibrium owing to internal stresses, when slip takes place this equilibrium is upset and a position of stable equilibrium is attained, in which the internal stresses have disappeared. This necessitates considerable slip taking place, such slip constituting the yield-point slip. This is nearly all internal, but is accompanied by some slight external slip to conform with the movement that has taken place in the crystallites.

While the crystallites are settling down into a position of equilibrium, the stress remains the same and the slip produces no hardening effect. That is to say, the piece cannot withstand any higher stress than S_2 without further slip. As soon as the equilibrium position is reached any further slip produces an increase in S_2 . That is to say, to produce further slip the stress must be increased, and with each increasing slip there is an increase in the value of S_2 . However, the slip that takes place is partly internal and partly external, the proportion of external to internal increasing as the slip increases. Thus hardening is due partly to the increase of S_2 and partly to that of S_3 . Though the initial value of S_2 is less than that of S_3 , the former increases with slip more rapidly than S_3 , so that a point is reached when the value of S_2 is equal to the value of S_3 . As the values of S_2 and S_3 approach each other, the ratio of external slip to internal increases until, when S_2 and S_3 are equal, the slip becomes wholly external. This continues until the breaking point is reached. The breaking stress may be equal to S_1 , but of that there is no evidence one way or the other.

This very brief account of hardening is a simple interpretation of the stress-diameter curve, and from lack of data is all that can for the present be offered.

There are two points of which no attempt at explanation

has been made. The first is the change in direction of the curve for hardened and tempered steels ; the second is the form of the equation ; that is why the stress varies as the diameter of the piece, or if the equation be put into the form of the stress-strain curve, why the stress should vary as $(1 + x)^{-\frac{1}{2}}$.

The solution of this last problem must be sought in the theory of probabilities. The slip planes in the crystallites and the crystallites themselves are arranged in every direction, and to get elongation in the direction of the stress the slip must take place in all directions.

The only way to calculate the relation between the actual amount of slip along the slip planes and the elongation is by having recourse to the theory of probability. The problem is an extremely difficult, if not impossible one, since not only can the slip planes lie in every direction, but the size and shape of the crystallites can also vary indefinitely.

GENERAL CONCLUSIONS.

In the tensile test, if the stress on the piece be plotted against the minimum diameter, the following equation is obtained for the portion between the yield point and fracture :

$$P = a - bd - e^{cd-f}$$

If the stress-strain equation be derived from the above equation it is :

$$P = a - b(1 + x)^{-\frac{1}{2}} - e^{c(1+x)^{-\frac{1}{2}}-f}$$

The term bd represents the hardening due to the external slip, and the term e^{cd-f} that due to internal slip.

For any steel under different heat treatments b does not vary greatly, while c varies considerably.

The total possible internal hardening, that is, e^{c-f} , is practically constant for a given steel.

The total possible external hardening, b , is always much greater than the value of e^{c-f} .

Owing to the yield-point slip the total possible internal hardening is never obtained, and similarly the total possible external hardening could only be obtained if the diameter of the test-piece could be reduced to zero without fracture.

The values of a , b , c , $c - f$, for similarly treated steels, increase arithmetically with the carbon content, the increase being greatest for c and least for $c - f$.

The position of maximum load on the curve occurs at a point where the hardening due to internal slip has practically come to an end. The hardening between the yield point and the maximum load is due chiefly to the internal slip, and is approximately constant for the same steel whatever the heat treatment.

Though the value of the maximum stress cannot be obtained directly from the equation to the curve, an empirical relation can be found between the maximum stress and the constants of the equation.

The diameter of the piece at the maximum load depends only on the internal slip, and varies greatly.

The decrease in diameter due to the yield-point slip has no relation found with the equation. This slip produces no hardening.

The curve, when produced backwards beyond the yield point, does not pass through the origin, but cuts the stress axis at a point which has no relation to the yield stress.

In cold-worked steels an equation is obtained which is identical with the equation for the unworked steel, if it is calculated on the diameter the steel possessed before it was cold-worked. If the equation is calculated on the diameter after cold-working, the curves when produced will meet the curve for the unworked steel in a point where $d = 0$, the slope of the curves giving a measure of the amount of cold-work that the steel has undergone.

Though the total data obtained are very small, yet the consistency of the results indicates that by this method quantitative values of the hardening by cold-work can be obtained.

I wish to thank the directors of Messrs. Steel, Peech & Tozer, Ltd., and Mr. E. H. Saniter, for permission to publish these results. I am greatly indebted to the staff of the Research Department at Messrs. Steel, Peech & Tozer, Ltd., for their assistance and interest in the work, especially the head of the Department, Dr. T. Baker, at whose suggestion I started the work; and Mr. T. F. Russell, Assoc. Met., and Mr. T. Bridgeland, who assisted me in the actual taking of the readings.

CORRESPONDENCE.

Dr. L. AITCHISON (Birmingham) wrote congratulating Mr. Stead upon his thoroughly interesting paper. In the account of the process of hardening by cold-work he described the stress required to produce internal slip, S_2 , as being the yield point stress. Should not that be the elastic limit stress? The behaviour of the material round about the elastic limit seemed to be much more simple than that at the yield point, and by definition the value called S_2 by the author would appear to be the elastic limit. Although that might appear to be a matter of words only it was of some more general importance. Very few metals showed a yield point, but practically all metals had an elastic limit. A theory of work-hardening, to be convincing, ought to be applicable, in at least its general features, to the majority of metals rather than to the minority. There might be a variation in detailed behaviour, but a major variation was difficult to understand. A theory depending upon yield point would seem to be unnecessarily restricted. If the author agreed with that opinion he might be willing to correct his account accordingly, or to show why the yield point was the stress that was of importance in iron and steel.

In the same account the author stated that external slip might take place without internal slip. He was referring here to the constituent crystals of the metal alone. It was noted that on p. 390 of the paper the statement was made that that view was supported by microscopic examination. The external slipping without any internal slipping of a crystal was difficult to understand. Presumably the crystals would have to slide past one another along their boundaries, and such a process was not particularly easy to visualise or to fit in with various considerations. For instance, during the cold-drawing of a wire did a stage occur at which the crystals of the steel slipped past each other? The formation of very narrow long crystals was difficult to understand on that assumption. Possibly the effects referred to by the author did not occur under such conditions, though since drawing might proceed to the extent of producing fracture of the metal, it would appear as though they ought. The author might think well to treat the point more extensively and to produce the microscopic evidence referred to.

Mr. G. M. BROWN (Sheffield) wrote that Mr. Stead's paper contained an immense amount of information in a very condensed form, but it was impossible to avoid some feeling of disappointment that the author had not succeeded in developing some simple general formula to represent the results of his labours.

The apparent necessity of plotting the curves on a base of decreasing diameter had complicated matters very much, and that method of plotting had not been adopted by Körber, who had recently published the results of a similar investigation.¹ His results were shown by curves with the percentage reduction of sectional area as abscissæ.

It was not easy to see why either method should yield curves which were practically straight lines once the point of maximum load was passed. If it were assumed, as suggested by Baker and Russell,² that the stress intensity of flow remained the same as the stress at the elastic limit, it would appear that curves plotted with abscissæ representing the logarithm of the strain should give some valuable information and be capable of representation by some simple formula.

Were the author's results plotted in the same manner as Körber's, the whole of his curves would terminate with a distinct convexity towards the axis of abscissæ, and only Körber's curves for soft steels with carbon 0.25 per cent. or less did so. The curves relating to higher carbon steels were practically straight, and if plotted in the same manner as the author's would be concave towards the axis of abscissæ and without any point of inflexion such as was shown in Fig. 6. The manganese, silicon, sulphur, and phosphorus were all much lower in the test-pieces used by Körber than in those used by the author.

The author's views on internal and external slip were interesting, but to one who had not had the same opportunities for the microscopic examination of test-pieces it was not easy to see why the internal slip should practically cease after a certain amount of cold-working, unless during that period the whole of the crystals had been subjected to internal slip, and so oriented that further internal slip became impossible. Tammann¹ asserted that the first portion of the permanent set in iron was due to external slip.

Mr. STEAD, in reply, wrote that he agreed with Dr. Aitchison that it would be better to define S_2 as the elastic limit stress. As he (Mr. Stead) was unable to determine that stress in his experiments, he defined S_2 in terms of the yield point stress which he did determine. The elastic limit stress might bear some simple relation to the equation. Such microscopic evidence as he had obtained was meagre and was only mentioned as pointing in the same direction as the interpretation of the equation. He would have liked to have made a fuller investigation in that direction, but had been unable to do so. He did not think that in wire-drawing the process was the same. He had been much disappointed not to be able to make tests on wire in the process of

¹ *Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung*, vol. iii. No. 2, 1922.

² "Note on the Ball Test," *Journal of the Iron and Steel Institute*, 1920, No. I. p. 341.

¹ Tammann, *Metallographie*, 2nd ed., p. 78.

drawing, and he shared, likewise, the disappointment, expressed by Mr. Brown, at not being able to develop some simple general formula. In fact he had spent the two years after the experiments had been finished in search of such a formula, but without avail, although he had tried plotting the results on the principle employed by Körber, but, as Mr. Brown pointed out, his results did not give a straight line relation such as found by Körber. Also he got no simple curve between the stress and the logarithm of the strain.

Some of the conclusions arrived at were difficult to understand, but it did not seem to him that the equation could be explained in any other way. Considering the complex structure of steel, he thought it rather remarkable that any relation should be found, especially such a consistent one as had been shown by his results.

Iron and Steel Institute.

SOME MECHANICAL PROPERTIES OF A SERIES OF CHROMIUM STEELS.

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(UNIVERSITY COLLEGE, SWANSEA).

THE present paper is a record of the effect of heat treatment on the mechanical properties of a series of chromium steels, consisting of two groups of steels containing about 0.35 per cent. carbon and 1 per cent. carbon respectively, the chromium content varying from 2 to 12 per cent. The most extensive examination of the mechanical properties of chromium steels yet published has been given by Sir Robert Hadfield,⁽¹⁾ who includes an excellent historical survey of the researches on chromium alloys with iron conducted previous to his paper. A review of this and of later work has recently been given by Edwards.⁽²⁾

In the paper by Hadfield, which is most closely connected with the present record, the samples were made by adding varying quantities of ferro-chrome to good wrought-iron scrap melted in clay crucibles. The ingots after pouring to the dimensions of $2\frac{1}{2}$ inches square were afterwards reduced by cogging and rolling to bars $1\frac{1}{8}$ inch diameter. He found difficulty in obtaining sound castings, due to honeycombing, and therefore added small quantities of aluminium and silicon. In all cases the carbon content was kept as low as possible, but as the chromium content was increased so also was the carbon content, by virtue of the fact that the ferro-chrome used contained 6 per cent. carbon. The chromium contents of the sample range from 0.2 per cent. to 16.3 per cent., the former having as little as 0.2 per cent. carbon, while the latter reaches the high value of 2.12 per cent. carbon.

As is realised by the author of that paper, it is very difficult to form a definite conception of the quantitative effects of the element chromium on the physical properties, due to the continued variation in the amount of carbon present. With regard to annealing, it is not easy to estimate the value of the physical

data produced for the treated specimens, as no details are given of the *modus operandi*; it can only be presumed that all bars were heat-treated alike, in which case a given treatment which would perfectly anneal one sample would certainly not produce the desired effect in all samples. It is also now well known that the rate of cooling is a factor of paramount importance; indeed, the high sensitivity of the properties of chromium steels to rate of cooling was even then realised by Arnold, as shown by his contribution to the discussion on the paper.

The two groups of chromium steels used in the present work contain but small percentages of foreign elements, and their analysis is given in Table I.

TABLE I.

Sample.	Chemical Composition.			
	Cr.	C.	Si.	M.
1	1.96	0.33	0.05	0.13
2	4.02	0.30	0.15	0.17
3	6.18	0.37	0.32	0.23
4	8.08	0.43	0.43	0.25
5	10.39	0.37	0.50	0.19
6	12.08	0.38	0.58	0.24
A	2.08	0.87	0.18	0.19
B	2.09	1.0	0.17	0.29
C	2.11	1.26	0.18	0.20
D	4.19	0.95	0.22	0.10
E	3.92	1.09	0.27	0.18
F	5.07	1.07	0.19	0.21
G	6.16	0.97	0.31	0.14
H	8.12	1.02	0.37	0.10
I	10.42	1.14	0.46	0.07

As already mentioned, the samples may be regarded as consisting of two groups, one with 0.35 per cent. carbon and the other with about 1 per cent. carbon. In the second group the amount of silicon present is very low, and nearly constant, except in samples G, H, and I; whereas in the first group there is a small progressive increase in the amount of this element.

PREPARATION OF SPECIMENS.

All the samples were originally in the form of 1 inch square rolled bars, and specimens of $5\frac{1}{2}$ inches length were cut and prepared for tensile tests. This initial preparation of the specimens in the lathe was a matter of some little difficulty and patience, particularly in regard to the lettered series, where B and C necessitated a very frequent grinding of the cutting tool. H and I were also very hard.

The usual form of test-piece was employed. The head was left square, the remaining portion of the metal being turned cylindrically in the usual manner, with a full 2-inch length of about 0.56 inch diameter, thus giving a cross-sectional area of a quarter of a square inch. Pips were punched for a 2-inch elongation determination, and also for an observation on the elastic property.

ANNEALING EXPERIMENTS.

The condition of the steels previous to annealing was as received, and being in the air-cooled condition after rolling may be regarded as semi-hardened.

A complete batch of the steels containing one of each of both series was annealed in a gas-fired muffle at 805°C . They were placed lengthwise in the furnace and tightly packed with silver sand to keep down oxidation to a minimum and to allow of a thorough annealing, the temperature being taken on a thread-recorder, with use of a platinum platinum-rhodium thermocouple. The time taken to heat up was four to five hours, and soon after the temperature was attained the furnace was turned off and the steels left undisturbed until the following day.

Even though tightly packed a certain amount of oxidation had taken place, and the sand had also fritted on to the steels, which were cleaned and prepared for the 2-inch tensile test. Unfortunately, it was not possible to fit a Ewing's extensometer in order to accurately determine the yield point, as the specimen did not give sufficient clearance between the pips and the grips in the machine, and the necessity for economy in use of the material prevented allowance being made for this factor.

Accordingly, the rough "dividers method" was employed conjointly with observations on the drop of the beam. In many cases the values of the yield point obtained are to a certain extent arbitrary to, say, 2 to 3 tons per square inch, owing to the difficulty encountered in deciding exactly just when the yield point was reached. This is due to the fact that these alloys do not exhibit the proportionality between stress and strain, according to Hooke's law, up to a certain point, followed by the usual more or less sudden increase in strain with the further application of but little stress, as in the case of an ordinary mild steel.

Table II. shows the values obtained on the $\frac{1}{4}$ -inch specimens calculated to tons per square inch.

TABLE II.—*Mechanical Properties of Annealed Steels.*

Specimen.	Annealed at 805° C.				Annealed at 850° C.				Annealed at 960° C.			
	Yield Point, Tons per Sq. In.	Tensile, Tons per Sq. In.	Elongation per Cent.		Yield Point, Tons per Sq. In.	Tensile, Tons per Sq. In.	Elongation per Cent.		Yield Point, Tons per Sq. In.	Tensile, Tons per Sq. In.	Elongation per Cent.	
1	...	46.8	26.6		25	45.2	26.5		18	34.8	23.4	
2	26.0	32.0	28.8		15	32.1	35.1		19	38.8	25.8	
3	38.0	43.9	25.0		16	36.6	34.2		21	40.2	25.0	
4	36.0	40.8	29.7		21	39.4	32.0		20	43.8	23.4	
5	18.0	41.2	31.2		20	42.7	27.3		24	42.6	25.8	
6	22.0	44.0	32.8		21	42.4	29.7		20	43.6	23.4	
A	24.0	48.6	20.3		25	44.3	30.5		40	61.0	8.6	
B	26.0	44.8	26.5		29	45.3	31.2		30	60.5	9.35	
C	28.0	47.6	26.5		28	50.0	23.4		30	54.5	18.7	
D	22.5	43.1	31.2		24	50.0	25.8		26	53.5	17.2	
E	25.0	56.4	20.3		24	52.2	19.5		42	58.9	3.1	
F	26.0	47.2	25.8		24	43.5	30.5		26	52.7	18.7	
G	27.0	49.6	32.6		24	47.1	26.5		24	44.4	26.5	
H	34.0	53.2	18.0		24	47.1	23.4		24	43.4	25.0	
I	21.0	34.8	34.4		16	33.3	32.0		18	32.3	28.9	

No yield point was noted for sample 1, and that recorded for sample 2 is not satisfactory, as no definite fall of the beam could be discerned, and only a gradual elongation noted by use of the dividers. At this point it was decided to take as the yield point that tonnage at which one point of the dividers had just crept out of one of the pips. This method of observation was not required

in some cases, as the yield point was at times noted with considerable precision by a sudden fall of the beam. The exact behaviour of all specimens during the tests was carefully recorded, but as nothing of importance is contained therein, this will not be referred to.

A further batch of the chromium steels was subjected to a similar annealing at 850° C. and, after cleaning, their mechanical properties examined. The yield point, tensile strength, and elongation are shown in the same table.

It was then decided to examine the effect of annealing the specimens at a much higher temperature, namely, 960° C., and this necessitated the heat treatment being applied to the two series of steels independently, as this temperature could be reached only in one of the small gas-fired muffles. The two groups were subjected, however, to an almost identical annealing—a slow raising of the temperature of the silver-sand packed muffle followed by an overnight cooling. The last three columns in Table II. indicate the properties for this temperature.

In this batch it was particularly difficult to decide on the load to take as representative of the yield point, especially in a few of the lettered samples.

QUENCHING EXPERIMENTS.

The mechanical properties of quenched specimens followed by tempering were then examined, each sample being given a separate heat treatment and subsequent quenching.

The method adopted to effect efficient quenching was as follows. One specimen at a time was heated in an electrically heated vertical tube furnace and was suspended by a length of nichrome wire attached to the head of the sample, the former resisting serious oxidation in the furnace atmosphere and retaining its toughness. The furnace itself was a nichrome-wound silica tube. In actually carrying out a quenching the current was turned on, with the external resistance adjusted for a maximum temperature of 960° C. in the furnace. When this temperature was reached the sample was introduced and maintained at this temperature for one hour, when a release of the supporting wire caused the test-piece to fall into a bucket of

mineral oil. The metal was vigorously agitated in the oil until quite cool. The temperature of soaking was recorded by means of a thermocouple resting on the head of the specimen while in the furnace, a check on the constancy of the temperature being effected with the aid of a thread-recorder.

Oil was used as the quenching medium owing to the fact that previous work on these steels had shown that in certain cases quenching cracks readily form. In a paper by Edwards and Norbury⁽³⁾ is inserted a note on quenching cracks relative to these steels, which states that "water-quenching above 900° C. gives cracks in most of them." Indeed, steels in the 1 to 6 series cracked very seriously when quenched from all temperatures above 900° C., whilst steels G, H, and I, those authors state, "did not crack with any of the quenching conditions applied." Further reference will be made to this.

No replacement of the furnace atmosphere with an inert gas was found to be necessary, as only a very small amount of surface oxidation was apparent, so long as the passage of an air current up through the furnace was prevented by stopping the lower end of the tube. No appreciable temperature gradient was noted in the particular portion of the furnace, *i.e.* the centre, where the samples were suspended.

On cleaning and subjecting a few of the steels to tensile tests, it was soon clear that cracks or incipient cracking had been produced by the operation of quenching. Accordingly, the remaining specimens were subjected to a one-hour tempering in a lead bath at 500° C., and, later, most of these to a further one-hour tempering at 650° C.

Each specimen was treated separately by immersing in molten lead—the higher temperature was the maximum which could be attained after well lagging the lead bath by packing round with asbestos sheet. After tempering, they were withdrawn from the lead and allowed to cool on an iron plate in the air. Again the test-pieces were polished up in the lathe. Table III. gives the results of tests conducted on specimens thus treated.

As indicated, numbers 1 and 2 broke in the shoulder, as also did A, hence B and C were tempered for one hour at 600° C.; the latter was badly pitted, due to oxidation, and broke in the

shoulder, obviously due to a crack. Later, cracks were observed in the polished heads of E and G.

TABLE III.—*Mechanical Properties of Quenched Steels.*

Specimen.	Heat Treatment after Quenching.	Tensile Strength. Tons per Sq. In.	Elongation per Cent.
1	Not tempered	44.0	Broke in shoulder
1	Tempered 1 hour at 610° C.	74.4	11.0
2	Not tempered	78.0	Broke in shoulder
2	Tempered 1 hour at 610° C.	56.3	18.7
3	Tempered at 500° and at 650° C.	60.4	17.2
4	" " "	59.2	18.0
5	" " "	56.4	17.2
6	" " "	60.1	18.7
A	Tempered at 500° C.	64.0	Broke in shoulder
A	Tempered 1 hour at 650° C.	56.0	" " "
B	Tempered at 500° and at 650° C.	85.7	" 6.25 "
C	" " "	31.0	Broke in shoulder
C	Tempered 1 hour at 650° C.	75.3	11.0
D	Tempered 1 hour at 500° and at 650° C.	73.5	7.0
E	" " "	81.0	11.0
F	" " "	75.8	12.5
G	" " "	49.0	Broke in shoulder
G	Tempered 1 hour at 650° C.	59.0	" "

BRINELL HARDNESS OF THE STEELS.

The hardness of the several specimens, after the various heat treatments, was examined by use of an Amsler hardness testing machine, with a 10-millimetre steel ball and a constant load of 3000 kilogrammes. The Brinell hardness numbers obtained from the dimensions of the diameter of impression are tabulated below (see Table IV., p. 426).

The last two specimens in the last column show a hardness after quenching from 1200° to 1300° C., whilst all the rest in the final column were quenched from 960° C. and treated in exactly the same fashion as indicated in the table showing the tensile results. In the first series, that is, for all specimens tempered at 805° C., the heads of the samples were cut off and indents made on the polished sawn surface as well as on one side ground free from oxide and subsequently polished. No difference in the hardness numbers was discernible between the two faces. It

was therefore taken as satisfactory to record future observations taken on one of the sides, ground and polished.

TABLE IV.—*Brinell Hardness Numbers.*

Specimen.	Brinell Hardness Numbers.			
	Annealed at 805° C.	Annealed at 850° C.	Annealed at 960° C.	Quenched in Oil. ¹
1	205	195	146	645
2	180	137	163	512
3	200	160	170	286
4	175	174	177	255
5	185	190	200	248
6	185	190	192	270
A	202	195	277	477
B	207	202	269	418
C	210	215	241	415
D	192	225	228	311
E	255	225	321	350
F	210	202	228	340
G	223	210	202	350
H	223	207	196	241 ²
I	153	143	140	255 ²

NOTE ON QUENCHING.

A glance at Table III. will show that in some cases a true "tensile strength" was not obtained, due to fracture taking place prematurely in the shoulder of the test-piece; this also rendered the evaluation of elongation percentage worthless.

It is of interest that in the numbered series both 1 and 2 broke in the shoulder on testing after quenching, whilst the other four samples of this series, on tempering at 500° and 650° C. for one hour, broke in the usual manner with constriction and fracture.

The ready tendency of this series to incipient cracking with any quenching operation, as previously remarked upon, would lead one to expect trouble in the tensile machine, yet none such was met with in 3, 4, 5, and 6. Certainly the initial stresses set up in the alloys by quenching are largely, if not entirely, removed by the tempering, but that cracks were almost certainly present

¹ These hardness numbers were obtained subsequent to the tempering indicated in Table III.

² Quenched from 1200° to 1300° C.

was clear from an examination of specimens 1 and 2. In both these alloys the cause of fracture was manifest, as shown by a dark annulus round the fractured parts.

It was after a test had been carried out on A that it was decided to raise the temperature of tempering from 500° to 650° C.; hence the major portion of the batch received a double tempering treatment. Even with this severe easing of quenching stresses, C and G broke in the shoulder. In an endeavour to obtain complete figures for the whole series, repetitions on quenched specimens were carried out, with the results shown in a previous table (Table III.).

Again the efforts with regard to A and G were unsuccessful, so were abandoned.

CONSIDERATION OF EXPERIMENTAL RESULTS.

The physical properties which have been determined in this work are diagrammatically reproduced in Figs. 1 to 4, each chart containing the complete data obtained for the whole series of steels after heat treatment at the temperature stated. The points as plotted along the abscissa are arranged in order of samples indicated in Table I., which represents an increase in chromium content in the two separate series of approximately constant carbon content.

From Fig. 1 it is observed that in the low-carbon steels the addition of chromium from 2 up to 12 per cent. has little effect on the tensile property, when such steels have been annealed at 800° C.; the marked exception is obtained with the sample containing 4 per cent. chromium. A slight general increase in elongation is noticed, whilst the Brinell hardness varies within not wide limits. In the high-carbon series the high tensile strength given with sample E may be noted.

The properties obtained with samples annealed at 850° C. show that there is a gradual increase in the tensile from specimen 2 to E across the two series; the hardness takes a similar course, and an increase in strength is accompanied by a fall in elongation percentage. The third diagram exhibits the profound change which has taken place in the properties of certain of the steels. In the first series there is a steady rise in tensile strength,

yield point, and hardness, the percentage elongation remaining almost constant; the second series, with the exception of E, shows a gradual fall in the tensile and in hardness, with increase in chromium content.

The last figure (Fig. 4) constitutes an incomplete series of tests on samples quenched at 950° C. in oil and then annealed.

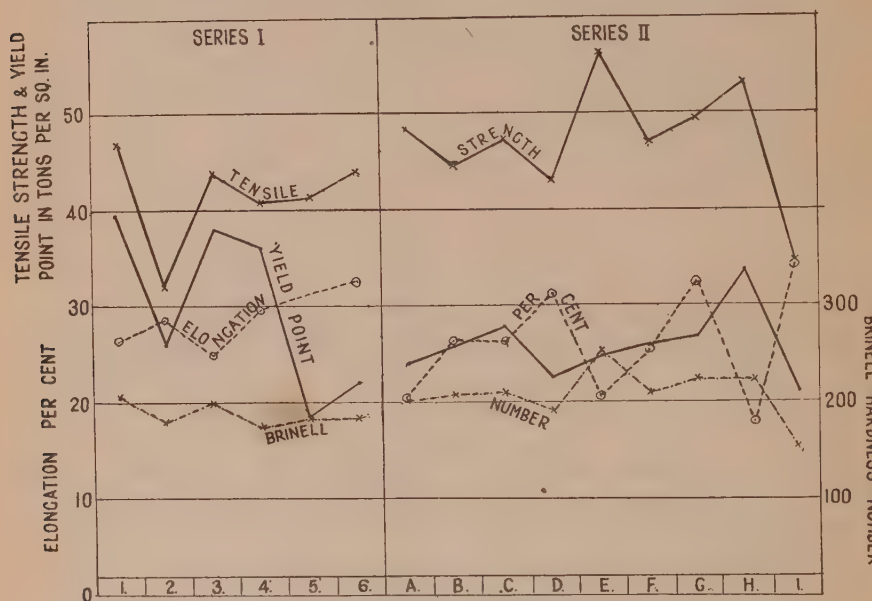


FIG. 1. ANNEALED AT 805°C.

A general consideration of each of the diagrams, and particularly those illustrating the properties after annealing at 800° and at 850° C., indicates that there do not appear to be any boundaries marking ranges of composition where any very abrupt change in properties is obtained, which is in agreement with the observations noted by Monypenny,⁽⁴⁾ who states that "No evidence has been obtained that chromium steels can be divided up into a number of areas of composition the properties of which differ from each other, owing to the presence of different double carbides." Certain evidence is, however, obtained by the present author when the temperature of annealing is raised to 960° C. A collective comparison of the four charts affords very con-

siderable interest, and provides facts which it is believed have not hitherto been noted and which do not appear to lend themselves to a satisfactory theoretical explanation on our present knowledge of the constitution of iron-chromium-carbon alloys. In Table V. are given the temperatures at which the carbide transformation occurs ¹ both on heating and on cooling.

TABLE V.

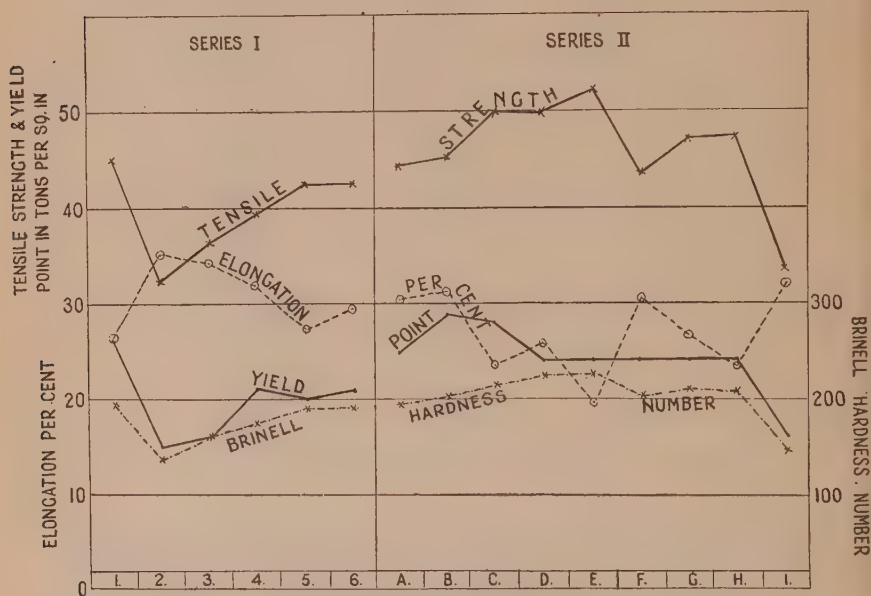
Sample Mark.	Ac1 on Heating.	Ar1 on Cooling.
1	797° C.	743° C.
2	817° C.	764° C.
3	833° C.	768° C.
4	833° C.	774° C.
5	835° C.	764° C.
6	830° C.	762° C.
A	792° C.	757° C.
B	790° C.	748° C.
C	774° C.	745° C.
D	801° C.	767° C.
E	795° C.	757° C.
F	805° C.	767° C.
G	825° C.	785° C.
H	829° C.	794° C.
I	836° C.	800° C.

To obtain a complete annealing of these steels it should be necessary only to heat them to a temperature at about the Ac1 transformation and then slowly cool. Hence from the table it is clear that 1, A, B, C, and E should have been annealed by the first heat treatment. The data, however, show a slight fall in the tensile strength and hardness after annealing specimen 1 at 850° C., whilst a very marked fall in these properties, accompanied by a decrease in the elongation, is obtained by annealing at 960° C.; the tensile is reduced from 46 tons to 35 tons per square inch. Specimen A shows a slight fall in tensile, B remains constant, whilst C has a higher tensile strength when the annealing temperature is raised from 800° to 850° C.

The most striking features of the series of tests are obtained

¹ See Edwards and Norbury, *Journal of the Iron and Steel Institute*, 1920, No. I.

when the annealing temperature is raised to above 900°C . In the low-carbon series there is not any very marked change in the tensile and hardness, except in the steels with 2 per cent. chromium and with 4 per cent. chromium, the latter showing an increase in both properties. On passing to the second series a profound influence on the physical properties is manifest, the tensile of the first two, with 2 per cent. chromium, rising above

FIG. 2. ANNEALED AT 850°C .

60 tons per square inch, with the Brinell hardness rising correspondingly and the elongation being reduced from above 30 to below 10 per cent. Steel E, not very different in composition from D, is most remarkable in the manner in which its elongation approximates to zero, an increase of 7 tons in the tensile being accompanied by a fall from 20 per cent. to 3 per cent. elongation; the hardness changed from 235 to 330. Steels G, H, and I become softer at the highest annealing temperature.

With reference to the quenched specimens, the chief feature worthy of note is the persistence of the properties usually associated with quenched steels even after tempering for one hour

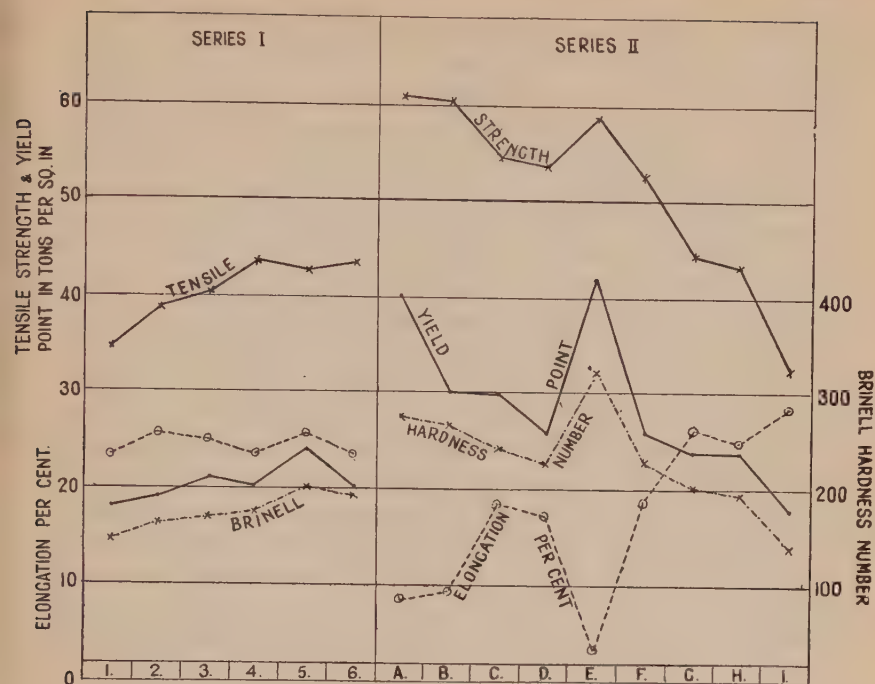


FIG. 3. ANNEALED AT 960°C

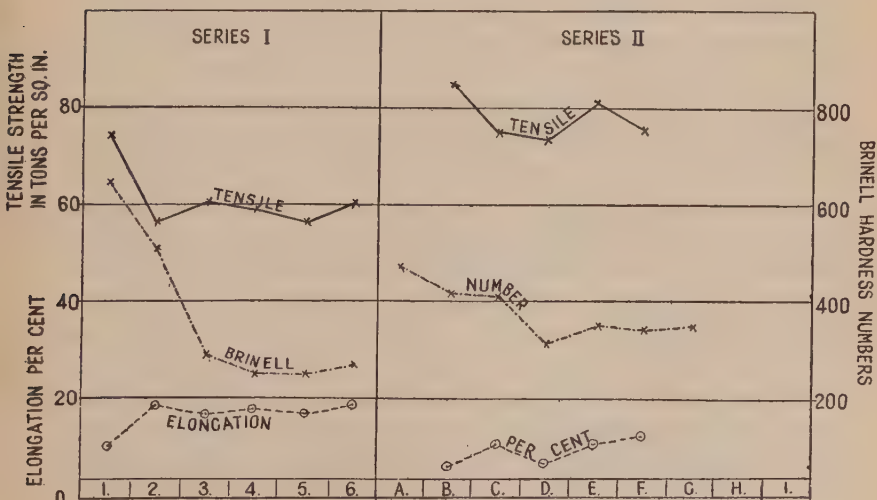


FIG. 4. QUENCHED AT 950°C

at 500° C., followed by a further tempering at 650° C. Resistivity determinations on these steels which have been tempered subsequent to quenching show that in the low-carbon series a minimum resistivity value was in most cases obtained at 700° C. or below. In the high-carbon series a minimum, representing a very considerable fall in resistivity, was always obtained on tempering at 650° C. This fact appeared to be independent of the quenching temperature, except in so far that the lower the quenching temperature the more readily was this minimum value obtained on tempering at temperatures below 650° C.

In the first series, apart from number 1, there is little difference in the tensile strength and elongation caused by varying the amount of chromium, but the magnitude of these quantities differs very considerably from those resulting from annealings at temperatures of 800° C. and upwards, and hence they do not fall into line with the electrical resistivity experiments. The divergence from the resistivity work is still further emphasised in the second series. Tempering at 650° C., after quenching, leaves the tensile strength in the vicinity of 80 tons per square inch, with a percentage elongation between 0 and 10. The Brinell hardness numbers are similarly high.

As previously indicated, it is not easy to find a satisfactory theoretical explanation of the very marked alteration in the mechanical properties of these steels when annealed at 950° C. and allowed to cool slowly, and the author refrains from theorising until more data are available on their constitution. This difference, however, in the influence of increasing the annealing temperature is in all probability associated with the fact that the nature of the carbides which are formed in the annealed steels changes with the initial temperature to which they are heated. A considerable amount of evidence which seems to indicate that this is the case has been put forward by Murakami.⁽⁵⁾ According to Murakami's magnetic observations, the character of the carbides more readily changes when the specimens are being heated to temperatures not far below those at which the carbides go into solution. It may be that the extent to which such changes occur on heating have a marked influence on the rate at which equilibrium is re-established after complete solution of the carbides.

Finally, it is of interest to refer to the age-hardening of quenched austenitic steel. A sample of I, which on quenching at above 1200° C. had given a Brinell hardness of 250, on leaving at atmospheric temperature for eighteen months increased in hardness to 420. In this connection reference may be made to the work of Brush,⁽⁶⁾ who has made extensive observations on the heat evolution at ordinary temperatures on recently hardened steels. He noted a heat evolution, greatest immediately after hardening, diminishing in ratio with time and becoming imperceptible after several weeks. The physical changes accompanying this spontaneous evolution were very small in comparison with those accompanying even slight tempering.

In conclusion, the author wishes to express his thanks to Professor C. A. Edwards, D.Sc., for suggesting the work and for providing all the material and facilities for carrying out the tests; the steels are similar to those on which he and his co-workers have published previous researches. He also desires to acknowledge his indebtedness to the Council of the Department of Scientific and Industrial Research for financial aid.

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- (1) HADFIELD, R. A.—“Alloys of Iron and Chromium.” *Journal of the Iron and Steel Institute*, 1892, No. II. p. 49.
- (2) EDWARDS, C. A., SUTTON, H., and OISHI, G.—“The Properties of Iron-Chromium-Carbon Steels,” Part I. *Journal of the Iron and Steel Institute*, 1920, No. I. p. 403.
- (3) EDWARDS, C. A., and NORBURY, A. L.—“Effect of Heat Treatment on Electrical Resistivity of Chromium Steels.” *Journal of the Iron and Steel Institute*, 1920, No. I. p. 447.
- (4) MONYPENNY, J. H. G.—“The Structure of some Chromium Steels.” *Journal of the Iron and Steel Institute*, 1920, No. I. p. 493.
- (5) MURAKAMI, T.—“On the Structure of Iron-Carbon-Chromium Alloys.” *Science Reports of Tôhoku University*, 1918, vol. vii. No. 3.
- (6) BRUSH.—*Bulletin of the American Institute of Mining and Metallurgical Engineers*, 1919, No. 153, p. 2389.

DISCUSSION.

Mr. J. A. JONES (London) said he had not been able to study very carefully all the results obtained by the author, but he would like to bring to his notice some work done by Dr. Moore at Woolwich about seventeen years ago, which was originally printed in 1907 and had since been reprinted and published as "Research Department, Woolwich, Report No. 35." This contained results of a very detailed examination of the mechanical properties of chromium steels containing up to 6.4 per cent. of chromium, with about 0.35 per cent. carbon, in the annealed and oil-hardened and tempered condition.

With reference to annealed steels, Dr. Moore found that up to 2.5 per cent. of chromium the maximum stress was raised and the elongation correspondingly reduced, but that with an increase of chromium over about 3 per cent. the maximum stress appeared to fall off. For purposes of comparison, it would be of interest if the author could give the rate of cooling between about 800° C. and 400° C. for the annealed steels. That was important when a comparison was made between the results given in the paper and those obtained elsewhere, on account of the fact that the critical cooling velocity of steel with a high chromium content was very low, as had been shown by Dr. Edwards in a previous paper.

He himself had done some work on chromium steels containing up to 3 per cent. of chromium, the results of which were given in "Research Department, Report No. 51." The qualities of such steels had been considered chiefly from the point of view of their commercial application, but a very full set of tensile tests was given.

There seemed to be some discrepancies between the figures given for Brinell hardness in Table IV. and for maximum load in Table II. Taking steel No. 2, the author had given a figure of 180 for the Brinell hardness of that material annealed at 805° C., while the corresponding figure for maximum load given in Table II. was 32 tons per square inch. As was well known, the Brinell hardness bore a fairly constant relation, depending on the yield ratio to the maximum stress. That ratio of Brinell hardness to maximum load, in the case of the particular steel in question, worked out at 0.177. Taking the case of the same steel annealed at 850° C., that had a Brinell hardness of 137 and a maximum load of 32.1, while the ratio worked out at 0.234. That was a difference considerably greater than anything which he had met with. There were similar differences in other cases.

The figures given for steels Nos. 1 and 2 in Table III. seemed rather strange. In the case of steel No. 1, tempered for one hour at 610° C., the author got a maximum tensile stress of 74.4 tons ;

with steel No. 2, containing higher chromium, with very slightly less carbon, he obtained a figure of 56·3 tons. He himself had examined a steel which corresponded fairly well with the author's No. 1, and with that steel, quenched in oil from 840° and given thirty minutes at 620° instead of an hour at 610°, obtained a maximum strength of 56·4 tons, which agreed fairly closely with the author's figure for steel No. 2. The figure of 74·4 tons seemed extraordinarily high.

CORRESPONDENCE.

Dr. L. AITCHISON (Birmingham) wrote that he had read Mr. C. R. Austin's paper with interest. He (Dr. Aitchison) had published a very considerable account of the mechanical properties of chromium steels in a paper to the Institution of Automobile Engineers,¹ and in a paper on valve steels to the same Institution had given a good deal of information on the same subject.² Apparently those papers had not come to Mr. Austin's notice. The results given in those papers appeared to be reasonably regular and conclusive. They were also very much more numerous than the results presented in Mr. Austin's paper. With the main result obtained by Mr. Austin, namely, that the mechanical effect of the addition of chromium to steel was approximately constant for all percentages over three—Dr. Aitchison was generally in agreement. The results in the papers quoted showed, however, that that was not absolutely true, and further showed that the effect upon the mechanical properties of the alloy of combinations of carbon and chromium was affected to some extent by the proportion of chromium.

There appeared to be very small grounds for choosing the particular heat treatments applied to the author's test-pieces. In particular it was not at all evident why 960° C. should be chosen as the quenching temperature for all the steels. Such a temperature was quite uncommercial, and, on the other hand, did not appear to rest upon any recognisable theoretical foundation. Even stainless steels were rarely heated in practice to that temperature before quenching. The methods of treatment adopted by the author were not calculated to produce the most satisfactory or most informative results with the steels. Similarly also the very various tempering treatments provided no regular basis for a comparison of the properties of the series of steels. It would be further of great interest to know why annealing was adopted as a suitable treatment to serve as a basis for comparison of the mechanical properties of the steels, and also why those particular

¹ *Journal of the Institution of Automobile Engineers*, vol. xvi. Part 1, p. 183.

² *Ibid.*, vol. xiv. p. 31.

annealing temperatures were chosen. Was it because annealing was never resorted to in connection with the practical use of those steels?

The Brinell hardness number given for steels 2 to 6 in Table IV. in the oil-quenched state were decidedly extraordinary, unless the samples were tempered at a fairly high temperature after quenching. If that operation had been resorted to, a statement to that effect might profitably appear in the table. If the specimens were not tempered, the results were so different from those obtained regularly in practice on stainless steels and those of the Quickstep type as to be almost unbelievable. Some explanation was very desirable. When oil quenched about 960°C ., steels of those compositions did not become sufficiently austenitic to give low Brinell values. Stainless steel, if hardened from about that temperature, regularly gave about 450 Brinell number, and Quickstep steels, even at 1000°C ., gave a Brinell number of about 600. The same values as those in Table IV. were shown in Fig. 4, and therein described as the hardened values. Dr. Aitchison's experience and published results were absolutely at variance with that particular set of values given by the author.

Sir ROBERT HADFIELD, Bart., F.R.S., Past President, wrote that he was greatly obliged for Mr. Austin's kind reference to his paper written in 1893, and was glad to find that it had stood the test of time, and was still thought to be of service when considering the qualities of iron and chromium. One of the reasons why that paper was written at that time was owing to the fact that Great Britain was largely dependent upon France for the supply of armour-piercing shell of the best quality. If those who had not read the paper cared now to refer to it, they would see that there was set out ample proof that the country was gradually rendering itself independent.

Successful progress had been made, and it might be interesting to state that to-day 16-inch armour-piercing shell of British make, and made by his (Sir Robert's) firm, were readily perforating unbroken 14-inch hard-faced armour inclined even 30° , at striking velocities equivalent to ranges of ten to twelve miles.

Referring again for a moment to the series of alloys he had described in 1893, naturally at that time, although the carbon was somewhat high, that was necessarily due to the higher carbon ferro-chromium then available. On the other hand, specimens of the test-bars in question, *i.e.* specimens J and L, had the following composition: 1176 J, carbon, 0.77 per cent.; silicon, 0.50 per cent.; chromium, 5.19 per cent. 1176 L, carbon, 0.71 per cent.; silicon, 0.30 per cent.; chromium, 9.18 per cent. In that respect he thought Mr. Austin's specimens were also somewhat high in carbon, that was, the first series varied from 0.30 to 0.43, and the second series from 0.87 to 1.26 per cent., that is, in some cases higher in carbon than the alloys he (Sir Robert) made in 1893. It might be interesting to prepare another series with carbon 0.10 per cent. or under. He (Sir Robert) would

be very pleased to collaborate with Mr. Austin in that respect, if he would care to carry out a research on such a series.

When speaking of alloys of chromium with iron, the name of Monsieur Brustlein, of Messieurs Holtzer of Unieux, France, should certainly be mentioned for the pioneer work he did in that direction.

What was the action of chromium upon steel? It seemed to him that indirectly it acted upon the carbon present. It would therefore be specially interesting to ascertain what were the qualities of alloys of iron and chromium in which the carbon was practically absent.

Mr. C. R. AUSTIN, in reply, said that he was pleased to have a contribution from Mr. Jones, and thanked him for drawing his attention to the research of Dr. Moore. With reference to the rate of cooling, Professor Edwards had shown, that within certain limits, that was immaterial when the ratio of chromium to carbon was less than 10 to 1, for such steels possessed similar hardening characteristics to ordinary carbon steels; the complete series of lettered steels fall within that category, and it was that series which provided the very marked increase in the value for the tensile strength when the annealing temperature was raised above 900°C . Only one tensile test on a sample of each steel annealed at 805°C . was taken, and the value given for the tenacity of No. 2 was possibly low, although no abnormality in the fracture was noticed.

The high tensile figure obtained for No. 1 after quenching and annealing, however, was supported by the evidence revealed in the low ductility represented by 6.2 per cent. elongation, as compared with 18 to 20 per cent. in the other steels of that series. It might be noted that the chromium-carbon ratio for that material was 5.9, and, from that point of view, was comparable with steels A to I; the ratio for samples 2 to 6 progressively increased from 13.4 to 31.8.

He thanked Dr. Aitchison for his contribution, and regretted omitting reference to his (Dr. Aitchison's) recent investigations. The omission occurred, presumably, because his research, and his reference to the literature, commenced before the publication of Dr. Aitchison's results.

With reference to the selected temperatures of annealing, little needed to be said so far as temperatures up to 850°C . were concerned, as that had been discussed in the paper. Dr. Aitchison asked if those steels were annealed at 960°C ., because such annealing was never resorted to in connection with the practical use of such steels. He (Mr. Austin) was not aware that he had been dealing with a series of steels which were commonly found in metallurgical practice, although some of the specimens were commercially employed. It might be stated with regard to the quenching temperature that that was intended to be one of a series of quenching temperatures, but it was not found possible to continue the work. A basis for the selection of that particular temperature, however, was indicated by the resistivity

data of Edwards and Norbury, who observed that it was necessary to attain a minimum quenching temperature of about 950°C . in order to obtain the maximum resistivity; in other words, to affect complete solution of the carbides. That temperature was low for H and I, and perhaps G, and unsuccessful attempts to quench the two former from about 1250°C . had not been mentioned. It was thought that the most interesting feature in that section of the work lay in the extremely high tensile strength which the samples revealed, even after one hour's tempering at moderately high temperature.

He (Mr. Austin) was in complete agreement with Dr. Aitchison on the apparently "decidedly extraordinary" Brinell hardness given in Table IV. for quenched samples, but that gentleman seemed to have rightly concluded that those hardness numbers were taken subsequent to the annealing which was employed before testing for tensile properties; the particular temperature and time of annealing were fully recorded in the previous table. A note had since been appended at the foot of the page on which Table IV. was included, indicating that fact.

Mr. Austin much appreciated the contribution of Sir Robert Hadfield. When making reference in the paper to the carbon content of the steels on which Sir Robert had done so much research, he (the author) had in mind the progressive character of the increase in carbon content, rather than the fact that any steel had a high absolute carbon value. He concurred that it would be extremely interesting to examine the physical properties of a series of iron-chromium alloys of very low carbon content, and would be very pleased to have the opportunity of collaborating in such a research.

Iron and Steel Institute.

THE Ac1 RANGE IN ALLOY STEELS.¹

By J. A. JONES, M.Sc. (RESEARCH DEPARTMENT, WOOLWICH).

NICKEL-CHROMIUM steels when heated at gradually rising temperatures and quenched in water show progressive hardening at temperatures considerably below the beginning of Ac1, as observed in heating curves taken by the usual method.² This effect has been mentioned by Brearley³ in connection with the tempering of nickel-chromium steels, and by Brayshaw⁴ when dealing with the hardening of steel containing 1.1 per cent. of carbon and 0.8 per cent. of tungsten. Very definite hardening on quenching from temperatures below the normal Ac1 was observed during an investigation of German gun steels⁵ of the approximate composition :

Carbon per Cent.	Manganese per Cent.	Nickel per Cent.	Chromium per Cent.
0.4	0.3	2.7	1.4

The curves in Figs. 1 to 3 show results of hardness tests made on one of these steels, (a) in the initially hard, (b) in the initially soft condition, and quenched in water after holding for various times at temperatures below Ac1. It was found that after holding the steel at a temperature about 20° C. below Ac1 (max.) and cooling in the furnace, the normal Ac1 point on heating showed two peaks (Ac1" and Ac1'). The lower point (Ac1") could be suppressed by quenching instead of slowly cooling from the temperature of soaking. Photomicrographs 1 to 3 (Plate XVI.) show the normal sorbitic structure of the hardened and tempered steel replaced progressively, with gradual increase of tempering temperature, by a structure consisting of ferrite and solid solution, while the changes in microstructure accompanying the progress

¹ Communication from the Research Department, Woolwich.

² Research Department, Woolwich. R.D. Report, No. 55, 1922, "The Properties of some Nickel-Chromium Steels," by J. A. Jones.

³ H. Brearley, "The Case-Hardening of Steel," 1921, p. 156.

⁴ S. N. Brayshaw, *Journal of the Iron and Steel Institute*, 1920, No. I, pp. 211-214.

⁵ Research Department, Woolwich. R.D. Report, No. 57, 1922, "German Gun Steels," by R. H. Greaves.

of hardening of the soft steel when heated at 730°C . and cooled in water are shown in photomicrographs 4 to 8 (Plates XVI. and XVII.). Assuming that isomorphous carbides occur in such steels it was suggested that, under equilibrium conditions, solution of the carbides would be accompanied by the formation of conjugate mixtures dissolving progressively through a range of temperature.

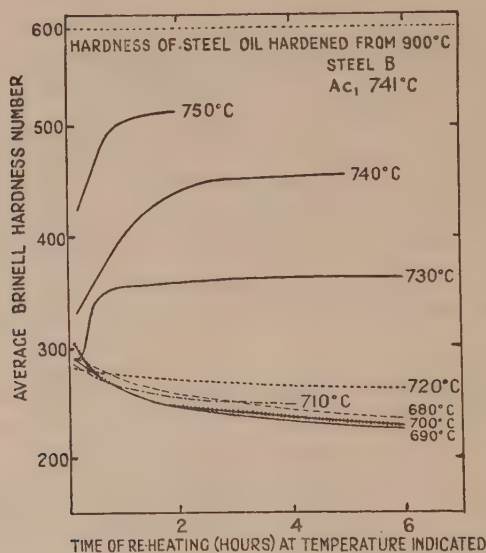


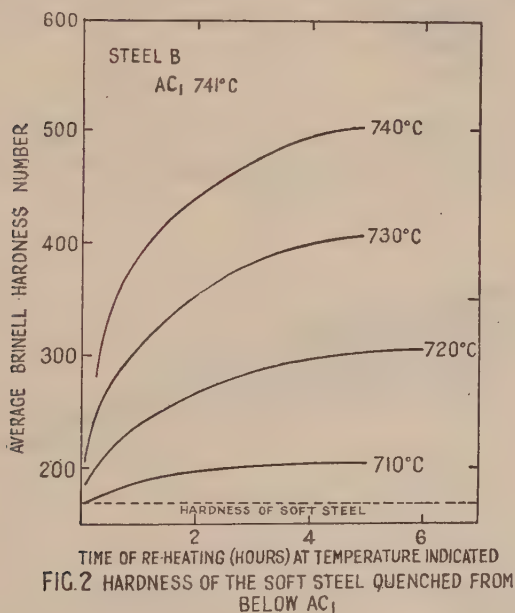
FIG.1 HARDNESS OF THE TEMPERED STEEL QUENCHED FROM BELOW A_{c1} .

The progressive hardening on quenching from temperatures below the normal A_{c1} has been investigated in nickel-chromium and other alloy steels.

The simple case of manganese steels will be considered first. Steels of approximately eutectoid composition and containing amounts up to 4.9 per cent. of manganese contain isomorphous mixtures of iron and manganese carbide $(\text{Fe}, \text{Mn})_3\text{C}$.¹ Fig. 4 represents a portion of the equilibrium diagram, in the vicinity of A_{c1} of manganese steels containing up to 4.0 per cent. of manganese or 0.8 per cent. of carbon.

¹ J. O. Arnold and A. A. Read, *Journal of the Iron and Steel Institute*, 1910, No. I. p. 169.

If A_{c1} occurs over a range of temperature in steels containing isomorphous mixtures of carbides, the lower limit of the range would be represented by a surface falling below ABC, shown in section by the dotted line BC and represented by ByC in Fig. 5. In this diagram B represents the temperature of A_{c1} in a steel containing 0.8 per cent. of carbon, C represents the limiting value of A_{c1} for an alloy containing 4 per cent. of manganese and



96 per cent. of iron, while the area enclosed by the two lines Bx_C and By_C shows the A_{c1} range in alloys of compositions represented by the line DE in Fig. 4, all of which are hypo-eutectoid steels. In taking heating curves by the ordinary methods the A_{c1} point observed approximates to, but is not necessarily exactly coincident with, the temperature represented by the top line. This line, Bx_C , is analogous to the liquidus in freezing-point curves of solid solutions, the lower line, By_C , analogous to the solidus is not readily detected by thermal means.

Take the case of a steel containing 0.4 per cent. carbon and 2.0 per cent. manganese represented by the middle point P of the

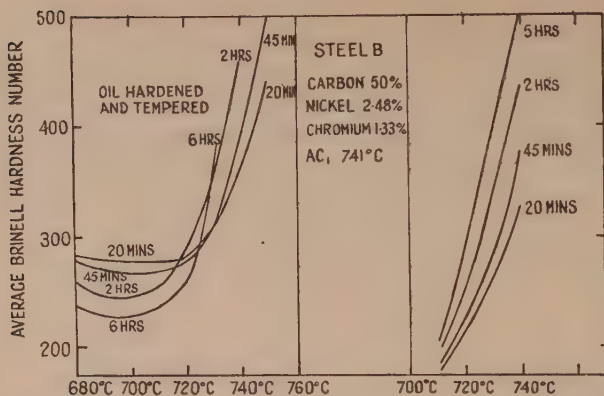
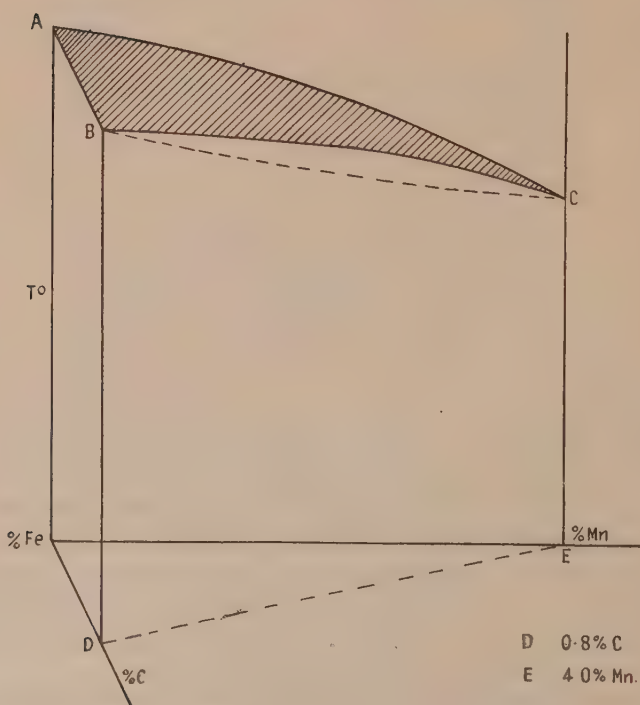


FIG.3. EFFECT OF TIME OF RE-HEATING AND QUENCHING TEMPERATURE ON HARDNESS

FIG.4 A_{c1} IN Fe-C-Mn ALLOYS

line DE in Fig. 5. A normal heating curve would give Ac1 approximately at the temperature t . If this steel, consisting of ferrite and an isomorphous mixture of iron and manganese carbides, is held at a temperature t_0 (p in Fig. 5) within the range, partial solution of the carbides occurs. The carbide which passes into solution is not of the same composition as the original mixture, but contains more manganese carbide, being represented by the point r . This leaves undissolved carbide, which approximates in composition to the point q as equilibrium is attained. If

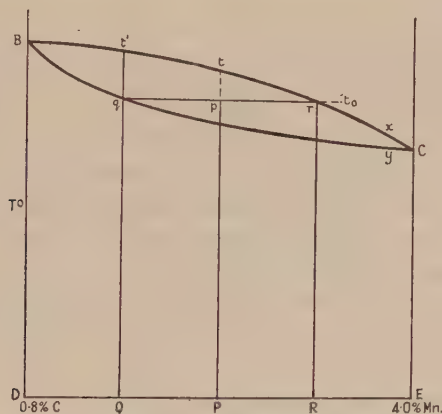


FIG.5. SECTION SHOWING AC. RANGE IN THE Fe-C-Mn DIAGRAM FIG.4.

without cooling the steel to a temperature at which the carbide in solution would be deposited, a heating curve is taken, a raised $Ac1'$ is observed at the temperature t' . If, on the other hand, the steel is cooled below the temperature at which the dissolved carbide is redeposited and a heating curve is then taken, two peaks are observed, the lower one, $Ac1''$, at a temperature t_0 , and the upper one, $Ac1'$, at t' . This effect depends on the fact that no appreciable diffusion of the partially separated carbides is possible in the time available at the temperatures employed, and the two conjugate mixtures of carbides of compositions Q and R preserve their identity under ordinary conditions of cooling. If heating of the steel P at a temperature t_0 has not been sufficiently prolonged, the two peaks $Ac1''$ and $Ac1'$ are not so widely separated, but with increasing time of soaking the lower point will remain at t_0 , while

the upper point will be progressively raised to the temperature t' , as the composition of the carbide left undissolved after soaking approaches the equilibrium composition Q.

A 2 per cent. manganese steel of the following composition was investigated :

Carbon per Cent.	Silicon per Cent.	Manganese per Cent.	Sulphur per Cent.	Phosphorus per Cent.
0.36	0.09	2.24	0.027	0.025

The variations in the position of Acl produced by previous treatment were :

		Acl (Maximum).	
Annealed.	Acl begins at 714° C.	721° C.	
Heated 3 hours at 689° C. cooled to 649° C. (above Ar1) . . .		729° C.	...
„ 1 hour at 709° C. „ 648° C. „ . . .		728° C.	...
„ 3 hours at 709° C. „ 528° C. (below Ar1) . . .		734° C.	713° C.
„ 6 „ 709° C. „ 535° C. „ . . .		736° C.	711° C.

The results are shown in Fig. 6 and curves Fig. 7.

In this and all other tables the temperature of soaking given is the *maximum* attained. It never fell more than 3° below the maximum during any treatment.

Referring to Fig. 5, after six hours' heating at a temperature t_0 equal to 709° C., Acl' is 711° C., approximately equal to t_0 , and t' (Acl') is 736° C.

The position of Ar1 was as follows :

		Ar1 (Maximum).
Cooled from 804° C.		604° C.
„ 709° C. after holding for 3 hours at that temperature . . .		600° C.

The results of investigation of other steels are given below.

CARBON STEEL.

Carbon per Cent.	Silicon per Cent.	Manganese per Cent.	Sulphur per Cent.	Phosphorus per Cent.
0.37	0.12	0.25	0.042	0.023

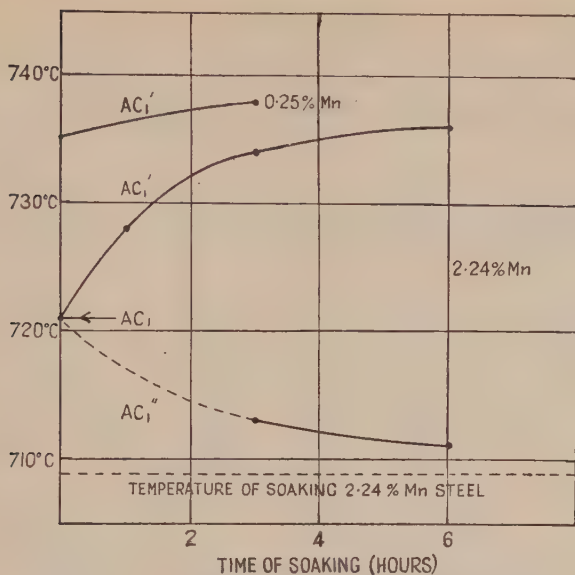
Variations in the Position of Acl produced by Previous Treatment.

		Acl (Maximum).	
Annealed.	Acl begins at 728° C.	735° C.	
Heated 3 hours at 720° C., cooled to 630° C.		737° C.	
„ 3 „ 723° C. „ 324° C.		738° C.	

The results are shown in Fig. 6 and curves Fig. 7.

Position of Ar1.

		Ar1 (Maximum).
Cooled from 842° C., Ar3 (max.) 771° C.		697° C.
„ 720° C. after 3 hours at that temperature		Not present

FIG. 6 CHANGES IN AC_1 AFTER SOAKING AT 12°C BELOW THE NORMAL POINT

2.24 PER CENT MANGANESE STEEL

CARBON STEEL (Mn 0.25 PER CENT)

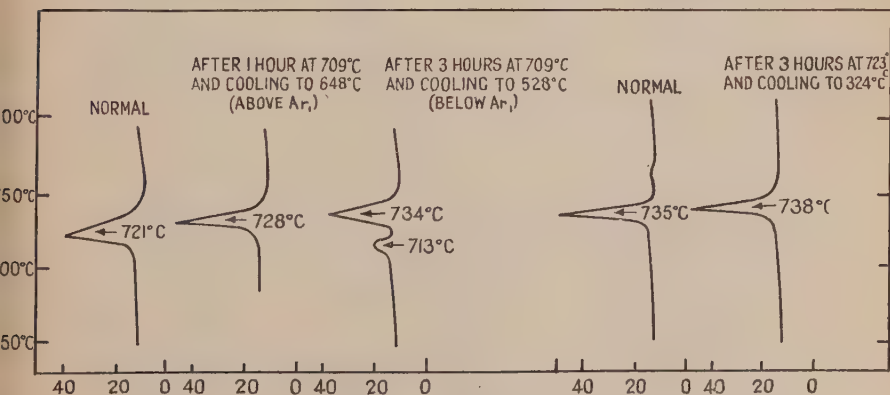


FIG. 7. HEATING CURVES

NICKEL STEEL.

Carbon per Cent.	Silicon per Cent.	Manganese per Cent.	Sulphur per Cent.	Phosphorus per Cent.	Nickel per Cent.	Chromium per Cent.
0.42	0.15	0.17	0.036	0.021	3.09	0.012

Variations in the Position of Acl produced by Previous Treatment.

	Acl begins at 695° C.	Acl (Maximum). 705° C.
Annealed.		
Heated 3 hours at 674° C., cooled to 644° C. (above Ar1) .		709° C. ...
„ 1 hour at 692° C. „ 644° C. „		708° C. ...
„ 3 hours at 692° C. „ 569° C. (below Ar1) .		711° C. 693° C.

Position of Ar1.

	Ar1 (Maximum). 627° C.
Cooled from 800° C., Ar3 (max.) 667° C. .	
„ 692° C. after 3 hours at that temperature .	620° C.

CHROMIUM STEEL.

Carbon per Cent.	Silicon per Cent.	Manganese per Cent.	Sulphur per Cent.	Phosphorus per Cent.	Nickel per Cent.	Chromium per Cent.
0.38	0.15	0.22	0.052	0.026	0.07	1.43

Variations in the Position of Acl produced by Previous Treatment.

	Acl (Maximum). 769° C.
Annealed.	
Acl begins at 761° C. .	
Heated 3 hours at 737° C., cooled to 686° C. (below Ar1) .	782° C. 765° C.
„ 3 „ 757° C. „ 638° C. „	782° C. 768° C.
„ 3 „ 757° C. „ 336° C. „	782° C. 767° C.

Position of Ar1.

	Ar1 (Maximum). 731° C.
Cooled from 831° C., Ar3 (max.) 754° C. .	
„ 757° C. after 3 hours at that temperature .	730° C. (approx.)

NICKEL-CHROMIUM STEELS. *Steel A.*

Carbon per Cent.	Silicon per Cent.	Manganese per Cent.	Sulphur per Cent.	Phosphorus per Cent.	Nickel per Cent.	Chromium per Cent.
0.43	0.13	0.69	0.021	0.027	1.96	2.15

Variations in the Position of Acl produced by Previous Treatment.

	Acl (Maximum). 747° C.
Annealed.	
Acl begins at 739° C. .	
Heated 3 hours at 714° C. cooled to 678° C. (above Ar1) .	750° C. ...
„ 3 „ 725° C. „ 678° C. „	753° C. ...
„ 3 „ 727° C. „ 614° C. (below Ar1) .	755° C. 735° C.
„ 1 hour at 734° C. „ 677° C. (above Ar1) .	751° C. ...
„ 2 hours at 736° C. „ 678° C. „	755° C. ...
„ 3 „ 735° C. „ 682° C. „	760° C. ...
„ 5 „ 736° C. „ 679° C. „	763° C. ...
„ 6 „ 735° C. „ 670° C. „	767° C. ...
„ 1 hour at 735° C. „ 624° C. (below Ar1) .	755° C. 741° C.
„ 3 hours at 735° C. „ 623° C. „	763° C. 739° C.
„ 9 „ 735° C. „ 195° C. „	774° C. 733° C.
„ 1 hour at 741° C. „ 679° C. (above Ar1) .	758° C. ...
„ 1 „ 739° C. „ 604° C. (below Ar1) .	760° C. 743° C.

The results are shown in curves, Fig. 8.

NICKEL CHROMIUM STEEL A (C 0.43, Ni 1.96, Cr 2.15 %)

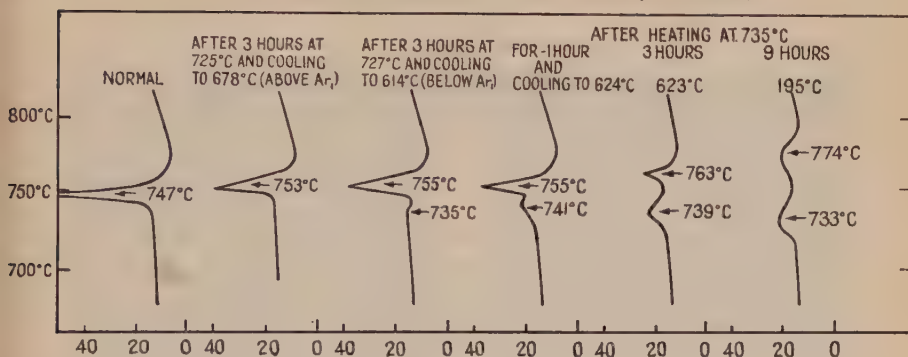


FIG.8 HEATING CURVES

Position of Ar1.

						Ar1 (Maximum).
Cooled from 803° C.	.	.	.	.	.	667° C.
Cooled from 727° C. after 3 hours at that temperature	.	.	.	.	.	Not detected
" 735° C. " 1 hour	"	"	"	"	.	654° C.
" 735° C. " 3 hours	"	"	"	"	.	644° C.
" 735° C. " 9 "	"	"	"	"	.	621° C.
" 739° C. " 1 hour	"	"	"	"	.	657° C.

The results are shown in curves, Fig. 9.

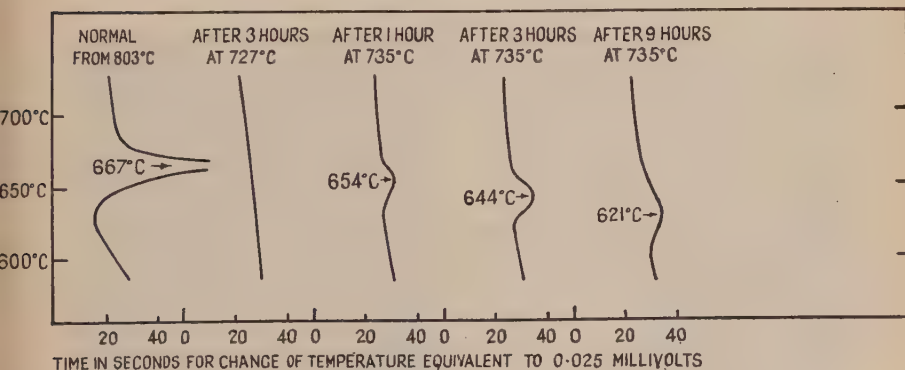


FIG.9. COOLING CURVES.

Steel B.

Carbon per Cent.	Silicon per Cent.	Manganese per Cent.	Sulphur per Cent.	Phosphorus per Cent.	Nickel per Cent.	Chromium per Cent.
0.50	0.28	0.31	0.045	0.016	2.48	1.33

Variations in the Position of Acl produced by Previous Treatment.

		Acl (Maximum).
Annealed.	Acl begins at 732° C.	741° C.
Heated 3 hours at 709° C., cooled to 683° C. (above Ar1)		745° C. ...
" 1 hour at 728° C. " 681° C. " "		744° C. ...
" 3 hours at 729° C. " 610° C. (below Ar1)		750° C. 736° C.

Position of Ar1.

		Ar1 (Maximum).
Cooled from 800° C.		668° C.
" 729° C. after 3 hours at that temperature		659° C.

Steel C.

Carbon per Cent.	Silicon per Cent.	Manganese per Cent.	Sulphur per Cent.	Phosphorus per Cent.	Nickel per Cent.	Chromium per Cent.
0.32	0.13	0.27	0.015	0.029	2.02	1.94

Variations in the Position of Acl produced by Previous Treatment.

		Acl (Maximum).
Annealed.	Acl begins at 742° C.	752° C.
Heated 3 hours at 718° C., cooled to 685° C. (above Ar1)		756° C. ...
" 1 hour at 738° C. " 685° C. " "		757° C. ...
" 3 hours at 739° C. " 685° C. " "		761° C. ...
" 3 " 739° C. " 609° C. (below Ar1)		764° C. 744° C.

Position of Ar1.

		Ar1 (Maximum).
Cooled from 808° C., Ar3 (max.) 683° C.		673° C.
" 739° C. after 3 hours at that temperature		667° C.

Steel D.

Carbon per Cent.	Silicon per Cent.	Manganese per Cent.	Sulphur per Cent.	Phosphorus per Cent.	Nickel per Cent.	Chromium per Cent.
0.54	0.10	0.17	0.051	0.016	2.11	2.09

Variations in the Position of Acl produced by Previous Treatment.

		Acl (Maximum).
Annealed.	Acl begins at 742° C.	751° C.
Heated 3 hours at 729° C., cooled to 711° C. (above Ar1)		752° C. ...
" 1 hour at 738° C. " 709° C. " "		752° C. ...
" 3 hours at 740° C. " 710° C. " "		759° C. ...
" 3 " 738° C. " 614° C. (below Ar1)		760° C. ...

Position of Ar1.

		Ar1 (Maximum).
Cooled from 803° C.		686° C.
" 738° C. after 3 hours at that temperature		680° C.

Steel E.

Carbon per Cent.	Silicon per Cent.	Manganese per Cent.	Sulphur per Cent.	Phosphorus per Cent.	Nickel per Cent.	Chromium per Cent.
0.37	0.18	0.70	0.012	0.033	1.93	0.62

NICKEL-CHROMIUM STEEL B.

Carbon 0.50. Manganese 0.31. Nickel 2.48. Chromium 1.33%.

 A_{c1} (max.) 741°C .Micros. 1—3. Re-hardening on quenching of the hardened steel at temperatures approaching A_{c1} 

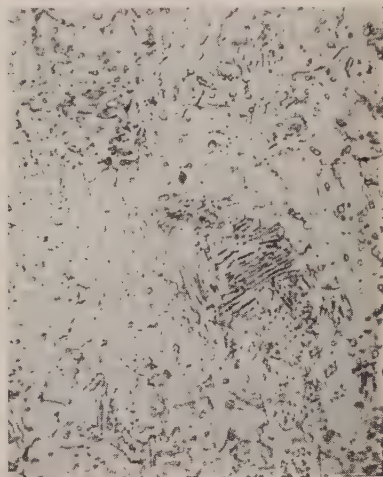
MICRO. 1. $\times 1000$.
Oil-hardened from 900°C . Re-heated
to 690°C . (2 hours) and quenched.



MICRO. 2. $\times 1000$.
Oil-hardened from 900°C . Re-heated
to 720°C . (2 hours) and quenched.



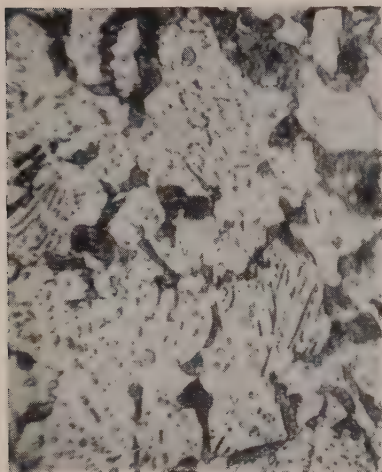
MICRO. 3. $\times 1000$.
Oil-hardened from 900°C . Re-heated
to 750°C . (2 hours) and quenched.



MICRO. 4. $\times 1000$.
Fully annealed.

NICKEL-CHROMIUM STEEL B.

Carbon 0.50, Manganese 0.31, Nickel 2.48, Chromium 1.33%.

 A_{c1} (max.) 741°C .Hardening on quenching after heating the fully annealed steel for various times at 730°C .

MICRO. 5. $\times 1000$.
Quenched after 15 minutes at 730°C .



MICRO. 6. $\times 1000$.
Quenched after 45 minutes at 730°C .



MICRO. 7. $\times 1000$.
Quenched after 2 hours at 730°C .



MICRO. 8. $\times 1000$.
Quenched after 5 hours at 730°C .

NICKEL-CHROMIUM STEEL E.

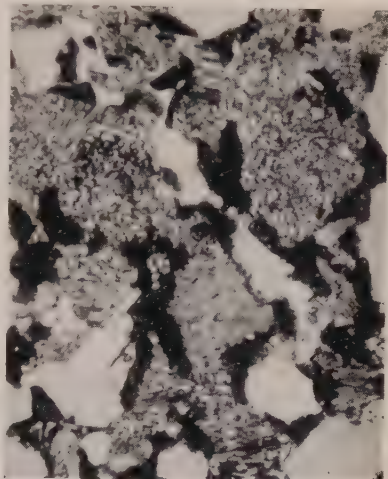
Carbon 0.37. Manganese 0.70. Nickel 1.93. Chromium 0.62%.

A_{c1} (max.) 728°C .

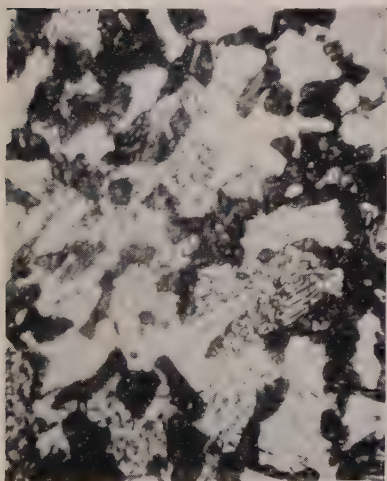
Hardening on quenching after heating the fully annealed steel for various times at 715°C .



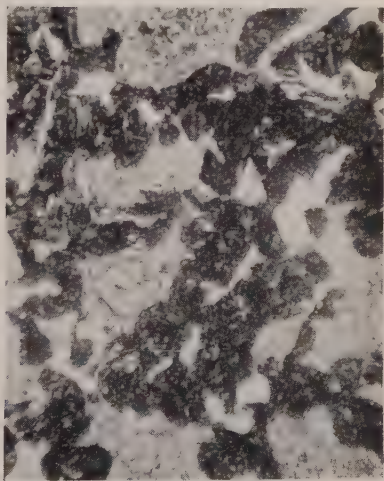
MICRO. 9. $\times 1000$.
Fully annealed.



MICRO. 10. $\times 1000$.
Quenched after 1 hour at 715°C .



MICRO. 11. $\times 1000$.
Quenched after 2 hours at 715°C .



MICRO. 12. $\times 1000$.
Quenched after 3 hours at 715°C .

Variations in the Position of Ac1 produced by Previous Treatment.

Annealed.	Ac1 begins at 719° C.	Ac1 (Maximum).	
		728° C.	
Heated 3 hours at 698° C., cooled to 665° C. (above Ar1)		731° C.	...
„ 1 hour at 714° C. „ 659° C. „ „ Ar1)		731° C.	...
„ 3 hours at 715° C. „ 595° C. (below Ar1)		741° C.	723° C.

Position of Ar1.

	Ar1 (Maximum).
Cooled from 813° C.	648° C.
„ 715° C. after 3 hours at that temperature . . .	645° C.

Photomicrographs 9 to 12 (Plate XVIII.) show the structures of this steel in the soft condition and also quenched from 715° C., after holding for one, two, and three hours at that temperature. The Brinell hardness was raised by these treatments from 197 to 252, 264, and 290 respectively.

From these results it is evident that the existence of an Ac1 range is common to a great variety of alloy steels. Data for determining the extent of this range are incomplete, but the results show that it differs considerably with composition. Fig. 6 shows the change of temperature of Ac1' as the time of soaking is prolonged at 12° C. below Ac1 (maximum) in the case of two steels containing 0.25 per cent. and 2.24 per cent. respectively of manganese. It will be observed that the low manganese-carbon steel shows a slight rise of Ac1', but no evidence could be obtained of any splitting of the point. This rise may possibly be an effect of the small amount of manganese present, or may be due to structural change in the form of the carbide. These conditions may operate in raising Ac1 in other steels, but only to an extent which is negligible compared with the total effect produced.

The resolution of the carbides into conjugate mixtures, one of which dissolves at the temperature of soaking, is completed slowly, and the rate of re-attainment of uniformity in the specimen outside the Ac1 range is dependent on the rate of diffusion of the carbides. If diffusion were rapid at temperatures below the Ac1 range, splitting of Ac1 could not be obtained. Even above the Ac1 range the identity of the conjugate mixtures of carbide is preserved, provided the specimen is not held for long at a temperature much above Ac1. It was found that if, after soaking, the steel were heated above Ac1 and then cooled, the cooling

curve in some cases showed two peaks where the normal cooling curve showed only Ar1 (Fig. 10). This may be due to deposition from solid solution of the carbide mixtures separately, or to the

NICKEL CHROMIUM STEEL

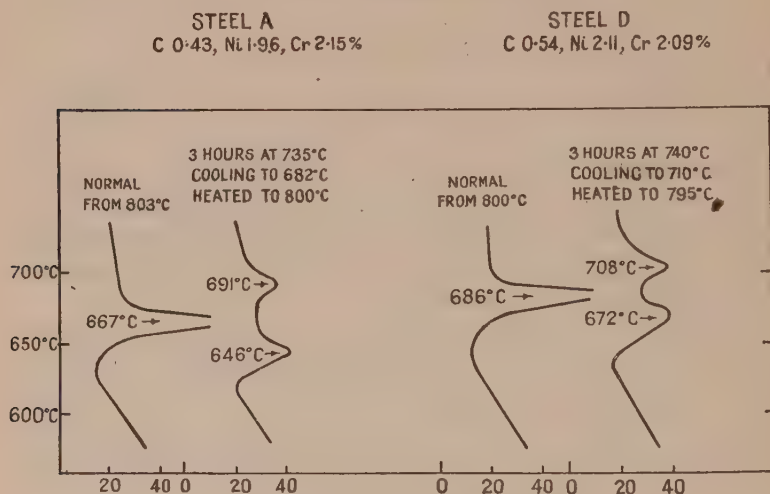


FIG. 10. COOLING CURVES

occurrence of the Ar3 point in some regions of the specimen. The behaviour, however, was very dependent on maximum temperature and time of heating.

SUMMARY.

In alloy steels Acl occurs over a range of temperature. Soaking within this range resolves the carbide into conjugate mixtures, one of which dissolves. This partial solution of carbide is associated with partial hardening on quenching and a corresponding change in microstructure. After soaking within the Acl range and cooling below Ar1 the steel will give two Acl points, one above and one below the normal point. If the steel is quenched from the soaking temperature, or is not cooled to Ar1, only the upper Acl point appears on the heating curve. In certain steels also, provided diffusion has not occurred above

Acl, a steel normally showing only Ar1 shows two points on cooling. Annealing restores the steel to its original condition.

In conclusion, the author wishes to express his indebtedness to Dr. R. H. Greaves for his continued interest and encouragement during the course of this work.

DISCUSSION.

Dr. D. HANSON (London) congratulated the author on the ingenious and very elegant way in which he had shown the changes which took place when steels, and especially nickel-chromium steel, were welded in the lower critical range. With regard to the fact that the lower transformation was a range in those steels and not a fixed point, he thought that had been shown very conclusively, although he did not know if it could be regarded as being anything very new; he thought all those who had been accustomed to deal with the steels in question had known that in ternary alloys that must be the case, and in heat treating, and especially in tempering (perhaps he should say overtempering), nickel-chromium steels those structures were not uncommonly found.

On the theoretical part of the paper, however, he was afraid he differed from the author very profoundly. The author's experiments did not, he thought, offer the slightest evidence in support of the theory that there were two carbides in the steels in question. The results obtained could be explained quite simply by a consideration of the equilibrium in a simple ternary system of alloys. Fig. 5 of the paper showed a section chosen, apparently, arbitrarily through the eutectic transformation. If the compositions of the alloys were plotted with the usual triangular base, it would be seen what the author had done.

The method of determining the composition of a phase of a ternary system of alloys was much more complex than the author supposed. The real explanation, as he (Mr. Hanson) saw it, was that the author had simply, in his alloys, one carbide, and the alloy in the slowly cooled state consisted of the ferrite plus that one carbide. The author took it up to successively higher temperatures, and passed it into the eutectoid range, and that one carbide began to dissolve and austenite formed. There was, therefore, ferrite plus carbide plus austenite, which was a perfectly possible thing. There was no reason to suppose there were two carbides; if it were taken to higher temperatures and allowed to set there would be rather more carbide dissolving. That was all; there were not two carbides at all.

He emphasised his objection to the author's work somewhat unwillingly, because the work had been done very carefully; but he thought it very important that it should not be suggested that two carbides existed in any of the systems in question, when the experimental results could be explained by assuming only one as present.

CORRESPONDENCE.

Mr. J. H. WHITELEY (Stockton-on-Tees) wrote that Mr. Jones had contributed a valuable piece of research work, but he (Mr. Whiteley) did not consider the explanation of the results obtained to be satisfactory. What was there to induce, so to speak, the carbide existing in the α -iron areas at Acl to change its constitution? Possibly the carbide dissolved in the γ -iron areas might change, but in the α -iron areas there appeared to be no reason for any alteration, such as the author supposed, to take place. Further, if the author's hypothesis were correct, should not a steel containing three elements capable of forming carbides give three arrest points at Acl instead of two as found? He suggested that the explanation of the duplicate points was really due to variations in the composition of the ferrite and not the carbide, brought about by the lengthy heating in the Acl range. Some time ago he (Mr. Whiteley) had endeavoured to show¹ that when ordinary hypoeutectoid steel was held between Acl and Ac3 some of its phosphorus diffused out of the γ -iron areas into the surrounding α -iron, with the result that, on cooling down, the ferrite was no longer homogeneous with respect to phosphorus. The same effect seemed to have occurred in the samples described in the paper, with, possibly, a similar redistribution of other elements besides phosphorus. The production of two ferrites in this way differing in composition would, of itself, give rise to two points at Acl when carbide was present in both. This explanation appears to be quite in accordance with all the evidence given in the paper.

Mr. J. A. JONES, in reply, thanked Dr. Hanson for his remarks, which he greatly appreciated. He was afraid, however, that Dr. Hanson had misapprehended some of the suggestions made in the paper, and some of his necessarily brief remarks were not quite so explicit as he could have wished. He (the author) had endeavoured to put forward an explanation of the observed facts in the light of the meagre information about the constitution of alloy steels at present generally available. In his opinion the most important fact established was the existence in slowly cooled steels within certain limits of composition of an isomorphous mixture of carbides. Dr. Hanson stated that those steels consisted of ferrite plus one carbide. If he meant one carbide of a single metal (e.g., Fe_3C) the author, in view of the work of Arnold and Read, could not agree. If he meant one single carbide phase, the author was in agreement; an isomorphous mixture was a single phase, it was referred to in the paper as "the carbide." After soaking in the Ac range, there was, as Dr. Hanson said, ferrite +

¹ *Journal of the Iron and Steel Institute*, 1920, No. I. p. 359.

carbide + austenite. It was the same carbide phase, but it was different in composition from that present in the steel before soaking. If the steel were soaked at a higher temperature, there would, as Dr. Hanson said, be rather more carbide dissolving; but that was not all. The composition of the carbides, dissolved and undissolved, would be different according to the time of soaking. He (the author) had found by electrolytic separation of carbide residues from (a) steels soaked in the Ac range and quenched, (b) the slowly cooled steels, that the residue from (a) was invariably poorer in the element giving the lower Acl point. The analysis of carbide residues was difficult to interpret, but the results clearly showed a change of ratio of iron to alloying element, and this he thought implied a differential solution of the constituents of the carbide.

Mr. Whiteley wrote as if a change of constitution of the carbide must occur before the $\alpha \rightarrow \gamma$ change. The change would occur, on the author's hypothesis, in the process of solution. An isomorphous mixture of salts treated with insufficient water to effect complete solution did not change in composition before dissolving in the water, or after, but in the process. The dissolved salt and the residue, originally identical, differed in composition. There was no reason to expect more than two points—there was one point corresponding to what went into solution, and another point corresponding to what remained undissolved after soaking, no matter what the chemical composition of those conjugate carbides might be. Though the phosphorus segregation referred to by Mr. Whiteley might go on, the author thought that the considerable differences in quantitative effect observed in steels of fairly similar phosphorus content, pointed to the preponderating influence of the carbide.

Iron and Steel Institute.

CHANGE OF DENSITY OF IRON DUE TO OVERSTRAIN.

By J. W. LANDON, M.A. (CAMBRIDGE UNIVERSITY).

THERE is considerable evidence that elastic failure occurs in ductile metals when the slide or shear strain exceeds a certain angle. After the elastic limit is reached, actual slipping occurs along cleavage planes inside the crystalline grains. According to Dr. Beilby's theory this slipping causes the molecules in the immediate neighbourhood of the cleavage planes to be broken free from their constraint, and actually during sliding there exists a fluid layer of the material. This fluid layer very rapidly solidifies, and since the molecules have not time to adjust themselves in the normal crystalline arrangement the material is left in an amorphous or vitreous state. Whether the material at the cleavage planes is actually amorphous, or whether it consists of very small crystals, is not of importance here, but for convenience the author will hereafter speak of the strained material as amorphous. Accompanying overstrain there is a change in the physical properties of the material.¹ The author has recently made an attempt to determine the maximum change of density of wrought iron which can be produced by overstrain. This appeared worth investigating, partly in connection with the amorphous theory, and partly on account of the fact that several writers have assumed that the density remained constant after the yield point. The chief difficulty in the investigation lies in the fact that in most methods of straining the actual magnitude of the strain at different points is unknown, particularly when the material is severely strained. To overcome this difficulty it was decided to use specimens in the form of cylindrical rods and to subject them to different amounts of axial twist. From considerations of symmetry alone, it is easy to show that in such a case particles originally in a plane section perpendicular to the

¹ "Aggregation and Flow of Solids," by Sir George Beilby, F.R.S.

axis will remain in a plane section, and also that particles which lie along a radius before twisting will remain on a radius after twisting. No sliding will occur on the cylindrical surfaces of the elementary tubes of which the rod may be considered built up.

Let θ be the angle of twist per unit length, and ϕ the angle of shear, or the slide, at a radius r . Then $\tan \phi$ will be equal to $r\theta$. Within the elastic limit, ϕ will be quite small,¹ and we may write $\tan \phi$ equal to ϕ .

Let us assume that up to a certain limit the amount of amorphous material per unit volume at each point varies directly as the slide in excess of that at the elastic limit—that is, as $(\tan \phi - \tan \phi_0)$, where ϕ_0 is the slide at the elastic limit. This appears a reasonable assumption, and, as will be seen later, it is justified by experiment.

The proportionality will only hold for angles of twist less than that at which the whole of the material at the boundary is changed into the amorphous state, or the maximum percentage of amorphous material is attained. There appears some doubt as to whether the whole material can be made amorphous by mechanical means.

Let the angle of twist per unit length at which the above state of things occurs be denoted by θ_1 . For values of θ less than θ_1 the amount of amorphous material per unit length of rod (q) may be represented by :

$$q = K \int_{\phi_0/\theta}^R (\tan \phi - \tan \phi_0) \cdot 2\pi r dr,$$

where R is the radius at the outside, and K is a constant for the material.

Writing $\tan \phi = r\theta$ and $\tan \phi_0 = R\theta_0$ we get,

$$q = \pi KR^3 \left(\frac{2}{3}\theta + \frac{1}{3} \frac{\theta_0^3}{\theta^2} - \theta_0 \right).$$

For the specimens used the value of R was $\frac{5}{16}$ inch, and θ_0 would be about twenty-six minutes. Neglecting the last two terms, which will be small compared with the first, we have :

$$q = \frac{2}{3} \pi KR^3 \theta \quad . \quad . \quad . \quad (1)$$

that is, the quantity of amorphous material per unit

¹ For wrought iron the value of ϕ at the elastic limit is about eight minutes.

length = $\frac{2}{3}\pi KR^3\theta_1$. For values of θ greater than θ_1 we shall have :

$$q = K \int_{\frac{R\theta_1}{\theta}}^R R\theta_1 \cdot 2\pi r dr + K \int_{\frac{R\theta_o}{\theta}}^{\frac{R\theta_1}{\theta}} (r\theta - R\theta_o) 2\pi r dr$$
$$= \pi KR^3 \left[\theta_1 \left\{ 1 - \frac{1}{3} \left(\frac{\theta_1}{\theta} \right)^2 \right\} + \frac{1}{3} \frac{\theta_o^3}{\theta^2} - \frac{\theta_o\theta_1^2}{\theta^2} \right].$$

We may neglect the last two terms since they are small compared with the others, and we get :

$$q = \pi KR^3\theta_1 \left\{ 1 - \frac{1}{3} \left(\frac{\theta_1}{\theta} \right)^2 \right\} \qquad \qquad \qquad (2)$$

q will be a maximum when $\theta =$ infinity, *i.e.* the maximum amount of amorphous material per unit length equals $\pi KR^3\theta_1$.

Let ρ_1 = the density of the material in the amorphous state,
 ρ_o = the density of the material in the crystalline state,
 ρ = the density of the material when strained.

$$q\rho_1 + (1 - q)\rho_o = \rho ;$$

that is, $q = \frac{\rho_o - \rho}{\rho_o - \rho_1}$

q varies, therefore, directly as the change of density due to overstrain.

EXPERIMENTS.

The material used was wrought iron, the chemical composition being as follows :

Carbon	.	.	.	.	.	0.058 per cent.
Sulphur	.	.	.	.	.	0.036 "
Phosphorus.	.	.	.	.	.	0.185 "
Manganese	.	.	.	.	.	0.255 "
Silicon	.	.	.	.	.	trace

The rods were turned down from $\frac{3}{4}$ -inch square bars to a diameter of $\frac{5}{8}$ inch for a length of about $9\frac{1}{2}$ inches. The ends of the rods were left square to enable them to be fitted into the torsion machine. After twisting, specimens of 2 inches in length were cut from the rods.

The actual densities of four specimens from each rod were determined, but only the results of the middle two specimens have been used, since it was found that the twist on the specimens

near the ends was not quite uniform, due to change in cross-section there.

The angle of twist of a specimen can be determined by scribing a line on the rod parallel to the axis before twisting and measuring the angle of the helix formed by this line. The angle may be drawn by rolling the specimen on waxed paper, such as is used for Roneo stencils, or by marking a few ink dots along the helix on the specimen and rolling on ordinary paper. In the case of the severely twisted specimens the original slag lines may be used in place of the scribed line. The results given were obtained from a series of readings, but are probably not of the same degree of accuracy as the densities.

The density of each specimen was determined by weighing in distilled water and in air, and readings were taken by two separate observers. The readings were taken with greater care and accuracy than was ultimately found to be necessary, as it had not been anticipated that the change of density would be so large. Only one complete set of readings need be given. The specimens were held in a small wire cage which was suspended from the arm of the balance by a fine platinum wire.

Specimen B₂.

Angle of twist per unit length = 225 degrees.

Weight of specimen in air = 75.3189 grammes.

Weight of cage and specimen in water = 67.8803 grammes.

Weight of cage in water = 2.4650 grammes.

Temperature of water = 10.4° C.

Density of water = 0.99969 grammes per cubic centimetre.

Weight of specimen in water = 65.3853 grammes.

Density of specimen at 10.4° C. = 7.5799 grammes per cubic centimetre.

Density of specimen at 0° C. = 7.5831 grammes per cubic centimetre.

The results obtained are given in the table on p. 459.

It was thought that in the case of the severely strained specimens the observed density might be in error due to air enclosed in possible cracks in the specimen. Under ordinary atmospheric pressure the entrapped air would prevent the water entering. To test whether that were so, a beaker of distilled water containing a specimen was placed in a vessel, and the pressure was reduced by a vacuum pump. The water boiled vigorously due to the reduced pressure, and any air entrapped should have escaped with the vapour formed. This treatment did not produce any substantial difference in the observed density.

The results given in the table are plotted in Fig. 1, and as anticipated from theoretical consideration, the graph is straight for small angles of twist, and becomes a curve for large angles

Angle of Twist. per Unit Length. Degrees.	Density at 0° C. Grammes per Cubic Centimetre.	Decrease of Density.
0	$\left. \begin{array}{l} 7.7150 \\ 7.7153 \\ 7.7144 \end{array} \right\} 7.7149$	...
70.5	$\left. \begin{array}{l} 7.6671 \\ 7.6642 \\ 7.6719 \\ 7.6680 \end{array} \right\} 7.6678$	0.047
150	$\left. \begin{array}{l} 7.6137 \\ 7.6151 \\ 7.6125 \\ 7.6131 \end{array} \right\} 7.6136$	0.101
225	$\left. \begin{array}{l} 7.5831 \\ 7.5813 \\ 7.5797 \\ 7.5767 \end{array} \right\} 7.5802$	0.135
262	$\left. \begin{array}{l} 7.5787 \\ 7.5787 \\ 7.5747 \\ 7.5705 \end{array} \right\} 7.5757$	0.139

of twist. The actual curve shown in the figure was obtained as follows :

The slope of the line given by equation (1) above was found from the first three points. These gave $\frac{q}{\theta} = 6.778 \times 10^{-4} \times \lambda$,

where λ is equal to $\frac{1}{\rho_0 - \rho_1}$.

The curve for angles of twist greater than θ_1 is given by equation (2). This has to touch the line given by equation (1). Equation (2) may therefore be written :

$$q = 6.778 \times 10^{-4} \times \lambda \theta_1 \times \frac{3}{2} \left\{ 1 - \frac{1}{3} \left(\frac{\theta_1}{\theta} \right) \right\} \quad (3)$$

Assuming the point for an angle of twist equal to 262 degrees has been correctly determined, equation (3) becomes—

$$0.1392 = 1.0167 \times 10^{-3} \times \theta_1 \times \left\{ 1 - \frac{1}{3} \cdot \frac{\theta_1^2}{262^2} \right\}$$

This gives $\theta_1 = 155^\circ$ and equation (3) becomes—

$$\rho_0 - \rho = \frac{q}{\lambda} = 0.1575 \left(1 - \frac{155^2}{3\theta^2} \right)$$

The curve shown was plotted from this equation.

If, then, the accuracy of the last point on the graph be accepted, the maximum change of density due to overstrain is

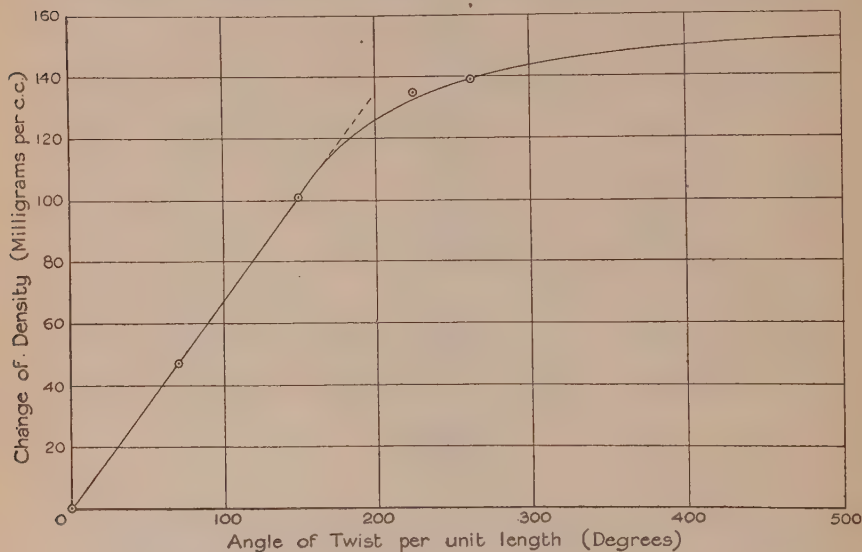


FIG. 1.

equal to 0.1575 gramme per cubic centimetre. It will be observed that the point for an angle of twist equal to 225° does not lie exactly on the curve. The observed value for the change of density is 0.135, and the curve gives 0.133. It is probable that the values obtained by experiment are not reliable to this degree of accuracy.

It was intended to obtain several more values of the change of density for different angles of twist. The greatest angle of twist obtainable was 262° , since any twist beyond this produced actual fracture on the outside at some section. Once fracture starts it spreads to the centre of the bar and the material is not all sheared through the same angle except in the region of the fracture.

After the above experiments were made, it was discovered that through a misunderstanding the remainder of the bar from which the test specimens had been cut had been used for other experiments, and no more of the material was available. Specimens were experimented with from another bar of wrought iron, the following results being obtained :

Angle of Twist per Unit Length. Degrees.	Density at 0° C. Grammes per Cubic Centimetre.	Decrease of Density.
0	7.7097	0
157°	7.6160	0.094
228°	7.5890	0.121

The points do not agree with those of the previous experiments, but the values of the difference in the change of density for the two different materials is probably due to the difference in composition, and to the different initial conditions of the materials. In both cases the material was used in the condition in which it was supplied by the makers.

It is hoped shortly to repeat these experiments, taking a larger number of specimens so that more observed points will be available for determining the true shape of the curve connecting the angle of twist per unit length and the change of density. It will also be advisable previously to anneal all the specimens under identical conditions.

The present experiments indicate that the maximum decrease of density due to overstrain for the material used is nearly 2 per cent.

Lowry and Parker¹ found that the density of iron filings was 0.49 per cent. less than the original iron from which they were made.

The author wishes to thank Mr. C. A. M. Thornton and Mr. E. D. Stansfield of Clare College, who took great trouble and care in determining the densities.

¹ *Journal of the Chemical Society*, 1915, vol. ii. p. 1010.

CORRESPONDENCE.

Mr. G. M. BROWN (Sheffield) wrote that the method adopted was ingenious and the results obtained were interesting, but it was to be regretted that the paper gave no information as to the magnitudes of the loads applied to the various test-pieces or their rates of variation with the strains they produced: in the absence of these figures it was impossible to calculate the amount of work done in the formation of the "amorphous" material.

A careful comparison of hard drawn and soft steel wires by Kahlbaum¹ indicated a maximum reduction of specific gravity of 0.25 per cent. in the hard drawn state. Similarly Goerens² found that by annealing hard drawn steel wire at a temperature of some 1080° C. the specific gravity was increased from 7.804 approximately to 7.824 approximately, a difference of the same order as that found by Kahlbaum.

In view of these concordant figures the author's result of a maximum reduction of specific gravity somewhere between 0.14 and 0.145, or nearly 2 per cent., seemed to require some explanation, and it would be interesting to know whether any precautions were taken to guard against the formation of incipient cracks and fissures in the surface layers of the test-pieces and the methods adopted for their detection.

As a result of careful measurements of tensile test-pieces, Baker and Russell³ concluded that the test-piece always fractured before the maximum cold-working effect could be attained, but according to the results recorded by the author the angle of torsion of the test-piece could be increased from 150° or 180° to 262° after the outer layers had been subjected to the maximum amount of distortion.

Mr. J. E. FLETCHER (Dudley) wrote that the results of the author's investigations were not surprising when it was remembered that wrought iron in bar form was the material investigated. It would be of interest and importance to compare the results with similar tests carried out on mild steel or Armco-iron rolled bars.

The mathematical determination of the amount of amorphous material per unit length of the rod, viz., that q varied directly as the change of density due to overstrain, depended on the elementary conception that the bar was built up of concentric tubes of infinitely small thickness.

That might be a true conception in the case of homogeneous material, but it would appear to the writer that the iron bar was better considered as a bundle of small longitudinally-parallel wires welded together imperfectly. When twisted, the outer layers of wires would

¹ *Zeitschrift für anorganische Chemie*, 1905, vol. xlv. p. 217.

² *Ferrum*, 1913, vol. x. p. 232, Fig. 250.

³ Note on "The Ball Test," *Journal of the Iron and Steel Institute*, 1920, No. I.

be elongated and each layer nearer to the axis of the bar similarly stretched though to a lesser extent, the innermost wire at the axis alone being twisted in accordance with the author's theory.

Such stretching of the bundle of wires, each wire of which would be reduced in diameter, would be accompanied by an increase of volume of the interstitial spaces, more especially between the outer layers of wires, or rather between the wires composing those layers. The piled structure of wrought iron, with its weak strands of slag, destroyed the possibility of regular crystal or amorphous grain slip, but would tend, under twisting test, to give the loosened structure of reduced density above mentioned. He (Mr. Fletcher) doubted the likelihood of a similar reduction of density in the case of mild steel or Armco-iron.

Dr. R. H. GREAVES (Woolwich) wrote that, as the author seemed to realise, the changes of density observed were extraordinarily large. They were greater than any he had succeeded in obtaining with steel, or remembered seeing recorded for any metal. The initial density of the wrought iron was abnormally low, implying a high content of slag, on the nature of which the chemical analysis did not throw much light. The presence of slag inclusions had been found to result in a certain lack of uniformity in the behaviour of wrought iron under overstrain; this was shown, for example, in the value of Young's modulus after restoration of elasticity. He suggested the possibility that slag inclusions were opened out in the interior of the specimen under torsional stress, causing internal cavities which affected the density. Such an effect would readily be detected by annealing all the overstrained specimens, and again determining the density.

He was glad to see that the experiments were to be repeated on annealed material, and hoped that a final annealing to restore the material approximately to its original condition would be employed to confirm the results.

Mr. J. W. LANDON wrote in reply that the twisting moments applied to the specimens unfortunately were not recorded. It was thought that they would have little value due to the fact that after the elastic limit is passed the strain is not quite definite for a given load, but varies with the time.

No special precautions were taken to guard against incipient cracks and fissures in the surface, but the effect on the density was investigated in the manner described in the paper. It was, of course, possible that twisting produced internal cavities in the slag regions which would reduce the density. The author proposed to adopt Dr. Greaves' suggestion to redetermine the densities after the overstrained specimens had been annealed.

Further experiments were now being carried out. Some, already made with Armco iron and mild steel, indicated that, as anticipated by Mr. Fletcher, the maximum change of density in those materials was considerably less than the change in ordinary wrought iron.

Iron and Steel Institute.

THE CHANGES IN IRON AND STEEL BELOW 400° C.

BY A. GOFFEY, M.Sc., AND F. C. THOMPSON, D.MET., B.Sc.

It has been shown quite recently⁽²⁵⁾ that in iron and steel at temperatures up to 300° C. a considerable number of change points occur, the existence of which has been demonstrated by electrical resistance and thermo-electric measurements. These changes appeared so remarkable that it was deemed necessary to confirm them. This has been done in the present research, which has also been extended up to 400° C. In addition the effect of the changes on the elastic limit has been determined.

Among the many investigations which have indicated the existence of one or more modifications of iron are the following: F. Robin, in a masterly memoir in 1910⁽¹⁾ on the physical properties of iron and steel at various temperatures, observed either maxima or minima at 200° C. and 300° C. In 1911 he published some work⁽²⁾ on the duration of sound emitted from steel when struck at various temperatures, and a decided minimum is instanced at about 120° C. In a paper in 1912⁽³⁾ he gives a general review and bibliography of the subject, and comes to the conclusion that static stresses indicate a point of transformation at about 100° to 250° C., while dynamic stresses indicate it at about 300° to 450° C.

Hardness determinations⁽⁴⁾ have indicated points of change at 100° and 250° C., while tensile strength and elongation show abnormalities at 100° C., 120° C., and 250° C.^(5, 6, and 7) The acoustic properties, as indicated above, have discontinuities at 120° C. and 250° C.^(2 and 8)

Charpy, and Guillet and Revillon have observed abnormalities in notched-bar brittleness^(9 and 10) at 150° C. A discontinuity in the velocity of sound through wires at 100° C. has been shown to exist by Wertheim, and Guye and Mintz⁽¹¹⁾ have recorded abnormalities in the viscosity of wires at 180° C. and 240° C.

Le Blant⁽⁷⁾ observed discontinuities in the tensile elastic

limit at 100° C. and 250° to 300° C., and Robin comments unfavourably on the use of this particular property for the purpose. As will be shown later, the authors are in disagreement with Robin on this point. Discontinuities in the magnetic properties have been shown to occur at 150° C. by Morris,⁽¹²⁾ at 180° C. and 300° C. by Maurain,⁽¹³⁾ and at 135° C. by Roget.⁽¹⁴⁾

K. Honda,⁽¹⁶⁾ following S. W. J. Smith,⁽¹⁵⁾ has done some careful work on the magnetic permeability of white cast iron, grey cast iron, and high carbon steel. A change was observed commencing at about 160° C. and completing invariably at 215° C. on heating; on cooling it invariably starts at 215° C. and finishes at about 160° C. The magnitude of the change was roughly proportional to the amount of free cementite, Fe_3C , present. Honda also observed a thermal change between 130° and 215° C. The temperature 160° C. in the magnetic change varied with the strength of the magnetising field.

Lea and Crowther⁽¹⁷⁾ observed a maximum in the tensile strength and yield point at about 300° C.

Lea⁽¹⁸⁾ obtained a maximum in the tensile strength of armco iron at 230° C., and a minimum in the elongation at about 100° C. and a maximum at 350° C. The elastic limit in tension fell to a minimum at 230° C. In a mild steel he got two discontinuities in the torsional rigidity modulus at 120° C. and 230° C.; in a 0.57 per cent. carbon steel discontinuities were also observed but were not particularised.

Dupuy⁽¹⁹⁾ has also observed maxima in the tensile strength and minima in the reduction of area at 250° in a 0.15 per cent. carbon steel, rising to 330° in a 0.91 per cent. and a 1.25 per cent. carbon steel, in which two the minimum in the reduction of area was unnoticeable.

Although all this work is very interesting, and has in general been very carefully executed, its value is to a large extent discounted by the fact that it has been done by a variety of workers on a variety of materials of which the analyses are often unstated, and under a variety of conditions. It is, therefore, impossible to state whether these discontinuities are all the same change occurring at different temperatures under the influence of different experimental conditions, or whether there is really more than one change operating. Also in the vast

majority of cases the work was not done as an investigation on these changes or abnormalities. The temperature intervals between readings were also excessive, of the order of 40° to 50° C., and this has the effect of masking the abnormalities.

Borelius and Gunneson⁽²⁴⁾ have published researches which are important in being the only other direct data obtained in the investigation of these low temperature changes in iron. The method employed was to compare the thermo-electric power of wires, quenched from gradually ascending temperatures and made into a couple, with an untreated wire. The values thus obtained were plotted against temperature. In their experiments they sometimes used the same specimen for each series of quenchings, and sometimes a different specimen for each test. The materials worked upon were wrought and high silicon irons, hydrogen-bearing electrolytic iron annealed in hydrogen, vacuum-melted electrolytic iron untreated and annealed in coal-gas, medium and high carbon steels, and high silicon iron annealed in coal-gas; all these show the points. This is noteworthy with the vacuum-melted electrolytic iron, as showing that the purest material available reveals these changes. They show that the gas content of the material modifies the curves, but that the most completely gas-free metal used still shows them clearly. On certain occasions the curves were carried over 900° C., and they still found these abnormalities persisting.

The curves thus obtained were decidedly irregular and were held to afford evidence of transformations in the iron which were designated Z changes.

The authors quite arbitrarily regard these as forming groups about a series of central points which they indicate as Z_3 , Z_4 , Z_5 . . .

They consider rightly that there is a periodicity about these points, and give an expression connecting the temperature with the numerical suffix to the point, which is of interest in that it is based on changes within the atom itself:

$$Tn = x + y \cdot n,$$

where Tn = the absolute temperature;

x = a small constant = 10—18;

y = a large constant;

n = the numerical suffix of the Z change;

i.e. Zn , where n is approximately the absolute temperature divided by 100.

They simplify this to

$$Tn = y \cdot n,$$

y being for iron 97, values for n running from 3 to 12.

To explain these results they assume that a Z change occurs when the number of atoms $\frac{1}{r}$ bearing a number of energy-quanta equal to or greater than the numerical suffix of the change, n , is a certain fraction, one-fourth, of the total. When one-fourth of the atoms have their respective number of quanta increased by one, a Z change results. This explanation, which involves no special characteristics in the material showing these abnormalities, requires that they should take place in matter of all kinds. Further, the "explanation" appears to the authors to be purely arbitrary and to have no physical basis. Borelius and Gunneson state that they have obtained evidence of this in tungsten, with a value for y of 81 and for r of 3.4, but they do not publish any curves.

Thompson and Whitehead⁽²⁵⁾ found no such abnormalities in the electrical resistivity of copper when fully annealed. There also appears to be no justification, in the curves of Borelius and Gunneson, for the grouping of several individual breaks into a single Z change. The work of the present authors, it is true, reveals an approximate periodicity, more, however, of the order of 50° than 100° , and, at its best, far from perfect.

The method of investigation pursued in the present research has been to select one physical or mechanical property and to determine its variation with temperature, any abnormality being regarded as indicative of some possible change in the metal. The effect of varying one condition while keeping the others constant was also ascertained. The first property to be examined was the electrical resistivity, which is the most convenient property for allowing minutely precise readings to be taken continuously over the entire temperature range. The torsional elastic limit has also been used to confirm and interpret the abnormalities in the electrical resistivity.

MATERIALS USED.

The materials used were: (A) Mild steel, (B) high carbon steel, and (C) electrolytic iron of the following analyses:

		C.	Si.	Mn.	S.	P.	W.
Mild steel	A	0.19	0.127	0.377	0.067	0.053	...
High carbon steel . . .	B	0.99	0.436	0.389	0.069	0.090	0.035
Electrolytic iron . . .	C	0.02	0.024	0.026	0.010	0.00027	...

A and B were received as annealed wire, but the electrolytic iron was received as two cylinders 1 inch long and $\frac{1}{2}$ inch diameter. These had been rolled from a 1 cwt. billet formed by welding up small pieces of electrolytic iron. There was in consequence quite a large amount of slag included, as may be seen from the microstructure. No pearlite could be detected, the structure being entirely polygonal grains of ferrite. One of these cylinders was cold-drawn into wire and was subsequently bright-annealed.

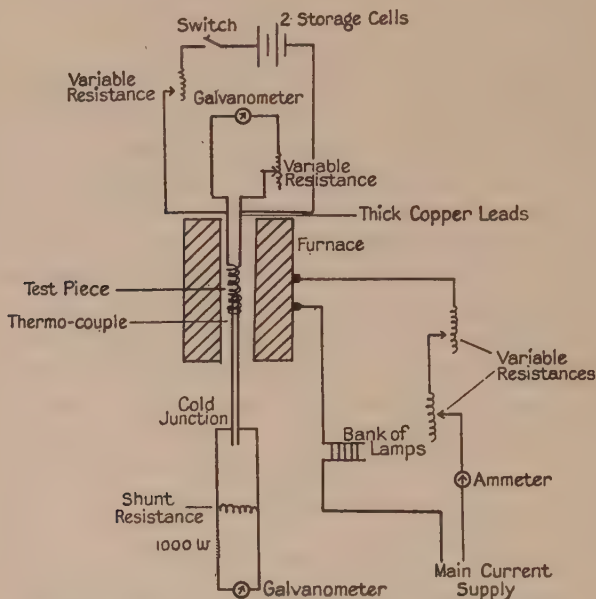
The steels, except for the high phosphorus and trace of tungsten in B, may be regarded as good quality commercial steels, while C is practically pure iron, the only perceptible impurities being manganese and silicon, which latter probably was present partly as slag.

EXPERIMENTAL DETAILS.

Owing to scarcity of apparatus and partly for the sake of convenience and simplicity, the resistivity apparatus constructed was of the direct reading type. A fairly heavy current of the order of 2 amperes was passed through the test-piece, a high resistance galvanometer being shunted across its extremities. Any fluctuation in resistance of the wire revealed itself as a change in the current flowing through the galvanometer (Fig. 1).

Actually, a length of 75 centimetres of the wire used was coiled non-inductively into a spiral 4 inches long, the extremities being brazed on to thick annealed copper leads about 30 centimetres long. These leads were insulated from one another by glass tubes for half their length. They were then bent away from one another and secured by clamps bearing on rubber tubing slipped over their extremities. The furnace used was of the electric resistance type clamped vertically to a retort stand. An exploration of the furnace at 350° C. showed a length of 6 inches of absolutely uniform temperature. The heating current, measured by an ammeter, was controlled by an elaborate system

of resistances, comprising a bank of eight assorted carbon filament lamps in parallel, a rheostat of maximum resistance 400 ohms going up in steps of about 25 ohms, and a sliding infinitely variable resistance of 50 ohms maximum; thus any



WIRING OF ELECTRICAL RESISTIVITY APPARATUS.

FIG. 1.

resistance between a maximum of about 2000 ohms and a minimum of about 40 ohms could be obtained. Very accurate temperature control was thus assured. Indeed any temperature up to 400° C. could be maintained indefinitely, plus or minus 2° C., with the exercise of a modicum of care.

Temperatures up to 360° C. were measured by a nitrogen-filled mercury thermometer of the type used in nitration pro-

cesses, there being a space of about 8 inches between the bulb proper and the 0° C. mark; thus the bulb could be placed within the resistance coil and yet the whole of the scale be without the furnace. It being later found advisable occasionally to exceed 350°, the original temperature limit, a copper-constantan thermocouple, calibrated by extrapolation from the thermometer, was introduced from the lower end of the furnace and the junction placed in contact with the bulb of the thermometer. The wires were insulated from one another by fireclay sleeves and from the coil by a fireclay sheath. The whole thermocouple assembly was led through a cork in the orifice of the furnace tube. The cold junction with the galvanometer leads was kept at room temperature by a jar of water.

The E.M.F. was measured by the direct deflection of a 40-ohm moving coil galvanometer, a spot of light being received on a scale. To reduce a deflection to manageable limits, 400° representing a deflection of 70 centimetres at 2 metres, a resistance of approximately 1000 ohms was placed in series with the galvanometer, the whole being shunted with about 1 ohm.

The current to the resistance coil was supplied by a 2-volt single-cell 60-ampere-hour accumulator and regulated by a 12-ohm sliding resistance, which had to be cleaned about once a week to prevent dirt and oxidation causing unforeseen fluctuations in current. Connections to the copper leads were made by screw bar-connectors, the shunt wiring to the galvanometer being connected at the same places. A plug switch was placed in the main circuit.

The shunt circuit consisted of a sensitive moving coil galvanometer in series with a post office box turned into a variable high resistance for the occasion. The deflection of the galvanometer was received as a spot of light on a 1 metre scale at a distance of slightly over 2 metres. Readings to $\frac{1}{2}$ millimetre were possible with the greatest of ease.

The resistances and galvanometer were adjusted so that, on making circuit at ordinary temperatures, the spot of light just swung on to the scale, and on heating to a maximum of 390° the spot moved right across the scale, the average deflection for 1° C. being about $2\frac{1}{2}$ millimetres. The furnace, resistance coil within the furnace, copper leads, thermometer, and a reading-lamp

for the last, were all clamped on to a heavy retort stand. Owing to an earth-leak of electricity, the above assembly was insulated from the table by a plate of paraffin wax, and all the insulation of the wires insulated from the earth by rubber tubing wherever it happened to touch any portion of the furniture or walls. Also the ammeter and all the resistances were insulated by india-rubber stoppers and tubing. This drastic treatment effectively killed any effect of the earth-leak.

Before any curves were taken on any particular coil, it was annealed to remove any effects of cold work and other abnormalities caused by the coiling and brazing. This was done by heating to about 370° to 380° C. in three hours and holding there for one and a half hours, and then cooling at a regular rate over a further three hours, the upper orifice of the furnace being closed by asbestos.

When taking a curve the circuit through the coil was made and the heating current was switched on, the resistances being adjusted to give the desired rate of heating; as the temperature rose the resistance was cut out at the right speed so as to maintain the rate of heating constant. The deflection of the galvanometer was recorded every 2° C.

On arrival at the maximum temperature the coil circuit was broken and the heating current adjusted so as to maintain the temperature at the particular value. In cooling down just the reverse procedure was adopted.

For each heating or cooling a curve was plotted showing the rate of increase of the deflection with temperature $\frac{\Delta\delta}{\Delta\theta}$ against temperature. •

This inverse-rate curve is well suited for revealing small discontinuities in resistivity as peaks; it is, in effect, the plotting of coefficient of resistance against temperature.

For the mild steel A the following heating and cooling curves were taken to investigate the effects of varying annealing time at 350° C. (Fig. 2.):

- A. 1. Heated to 350° C. during $3\frac{1}{2}$ hours, held there 1 hour, cooled during $2\frac{1}{2}$ hours.
- A. 2. Similar heating and cooling, but $1\frac{1}{2}$ hour at 350° C.
- A. 3. Similar, but 2 hours at 350° C.
- A. 4. Similar, but $2\frac{1}{2}$ hours at 350° C.

The rate of heating and cooling was in the region of 2° C. per minute.

To investigate the effect of varying heating and cooling rates the following curves were taken :

- A. 5. Heated to 350° C. during 10 hours, held there overnight during 14 hours, and cooled in 9½ hours.
- A. 6. Heated to 150° C. in 7 hours, held overnight during 17 hours, heated to 350° C. in 9½ hours, held overnight during 17 hours, and cooled down to 56° in 3 hours.

These, together with one of the previous curves, represented rates of approximately 2° C. per minute, 0.5° C. per minute, and 0.25° C. per minute.

Suspicion of one point at about 360° C. had arisen, so the following curve was taken to establish its existence :

- A. 7. Heated to 370° C. during 3½ hours, held there 1 hour, cooled in 3 hours.

To confirm or eliminate the possibility of dissolved gases causing any of these discontinuities, a coil was annealed in vacuum and used for the following curves :

- A. 8. Heated to 350° C. during 2½ hours, held there 1 hour, cooled during 2½ hours.
- A. 9. Heated to 360° C. in 2½ hours, held there 1½ hour, and cooled in 2½ hours.

All the above curves are seen in Fig. 2. For the high carbon steel B the following curves were taken (Fig. 3) :

- B. 1. Heated to 350° C. during 3 hours, held there for 1 hour, cooled during 3 hours.
- B. 2. Similar, but heated to 370° C.
- B. 3. Heated to 350° C. during 6 hours, held there overnight for 18 hours, cooled during 6 hours.
- B. 4. Heated to 210° C. during 6 hours, held there overnight for 18 hours, heated to 360° C. during 6 hours, held there overnight for 18 hours, cooled to 210° C. during 6 hours, held there overnight during 18 hours, cooled to room temperature during 6 hours.
- B. 5. On a vacuum-annealed coil, heated to 360° C. during 2½ hours.

On the electrolytic iron C the following curves were taken (Fig. 4) :

- C. 1. Heated to 370° C. during 2½ hours, held there for 1 hour, cooled during 2½ hours.
- C. 2. Heated to 200° C. during 5½ hours, held there overnight during 18 hours, heated to 360° during 5½ hours, held there overnight during 18 hours, cooled to 200° C. during 5½ hours, held there overnight during 18 hours, cooled to room temperature during 5½ hours.

Two heating curves were taken on quenched specimens, one

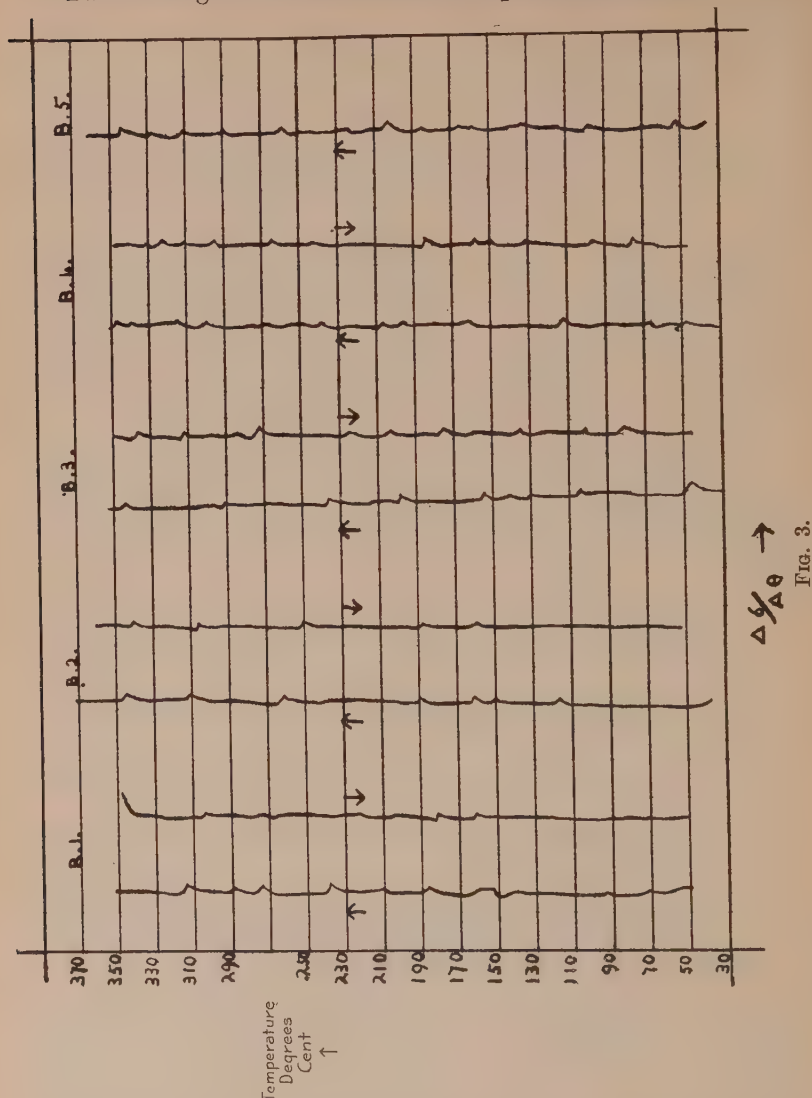


Fig. 3.

on the electrolytic iron C cool, and one on the high carbon steel B, as follows (Fig. 5) :

Bq. High carbon steel, $\frac{1}{2}$ hour at 390° C., quenched in air-blast in 4 minutes, heated to 360° C. in $2\frac{1}{2}$ hours.

Cq. Electrolytic iron, similar.

The curves for mild steel (Fig. 2) appear to become simpler with slower heatings. The fact that A. 7 is of the type A. 1, 2, 3, 4, rules out the possibility that the simplification was due to repeated

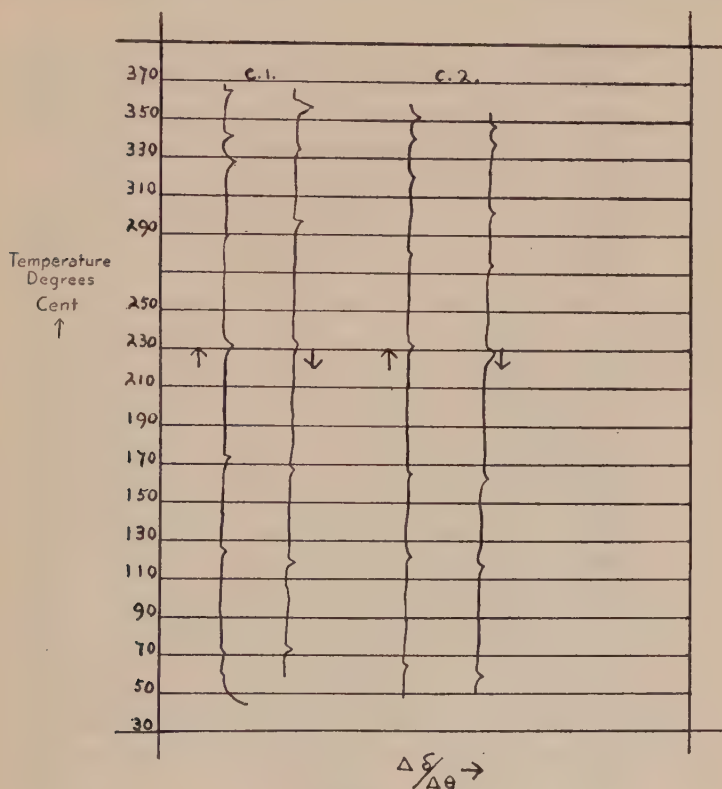


FIG. 4.

heatings, as it was taken after the simple A. 5, 6 curves, and has reverted to the old type.

The vacuum-annealing had no effect in eliminating any of the points. It was noticed, moreover, that the curve appeared more complex.

Well-defined discontinuities appear to occur at approximately 60° C., 120° C., 170° C., 260° C., 320° C., 360° C., and occasionally at 90° C., 200° C., 230° C. These values vary according to the rate of heating, &c.

After these points the value of $\frac{\Delta\delta}{\Delta\theta}$ appears to change, slowly at first and then permanently. Minor irregularities also occur which have no effect on this. In the high carbon steel the

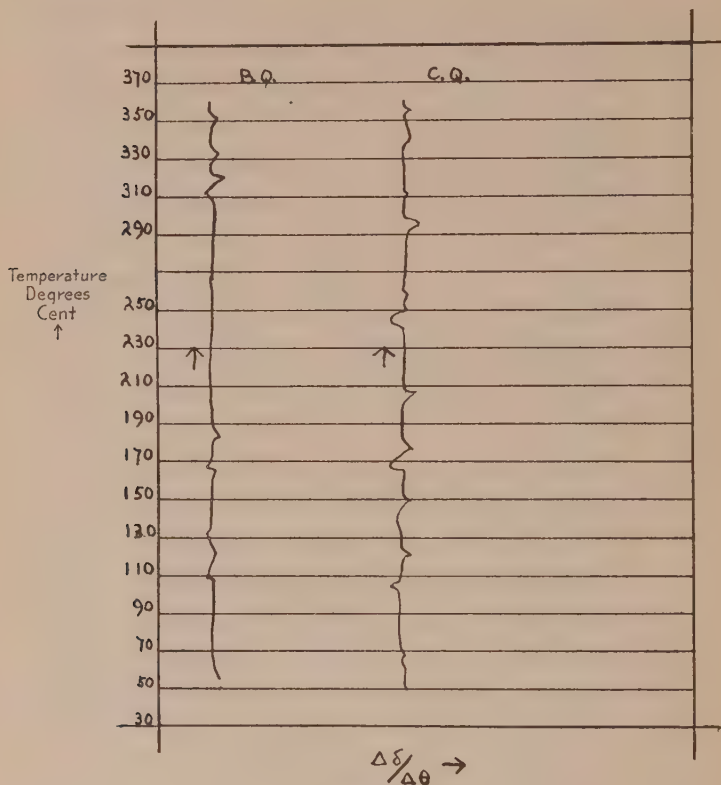


FIG. 5.

phenomena seem more complex; well-defined points occur at 50° C., 90° C., 120° C., 160° C. (often a double point), 200° C. to 190° C., 220° C., 250° C., 300° C., 350° C. The remarks on the mild steel apply equally to this.

The electrolytic iron C gave beautifully regular curves with peaks at 70° C., 120° C., 170° C., 230° C., 290° C., 310° C., 350° C. (usually a double peak). Marked thermal indications of the

points were noticed in B at 200° C. and 300° C., and in A and C at 300° C.

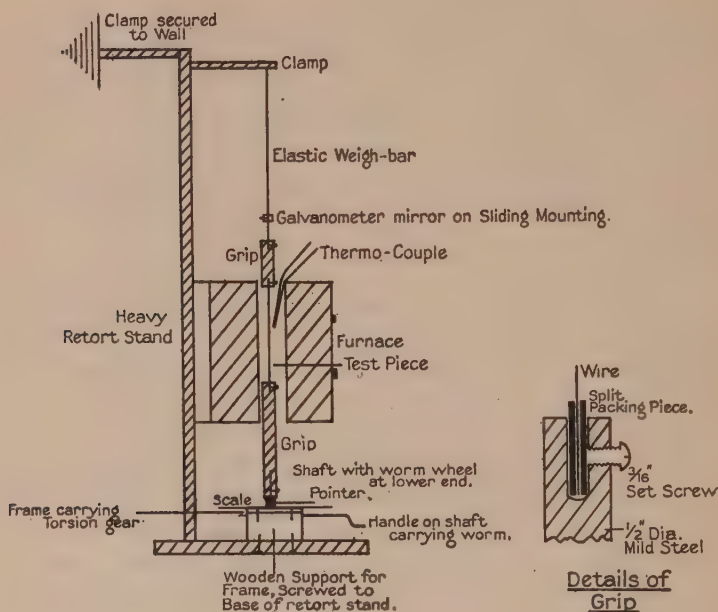
It appears that the large amount of carbide present in B tended to mask the results by slowing up the changes; this, however, will be discussed later.

The quenched specimens gave disappointing curves. Any outward peaks seemed to be balanced by corresponding inward peaks. This may be a tempering effect. There appeared to be no simplification, due to slower heating and cooling rates, in either B or C. In all cases slower heating reduced the hysteresis between the heating and cooling points. Varying the annealing time at the maximum temperature seemed without effect on the points.

In order to confirm and to interpret if possible the results, it was decided to determine some mechanical property at various temperatures within the range used. The test steels being wires, torsion tests suggested themselves. The ultimate stress was rejected as being a combination of unknown factors, and the elastic limit was chosen as being a more fundamental property. A machine was therefore constructed whereby data could be obtained for drawing stress-strain curves, from which to determine the limit of proportionality. In principle, the test-piece was attached at one end to gear for twisting it, and at the other to the end of a long steel wire of great section compared with the test-piece. When a torque was applied to the test-piece an elastic deflection was produced in this elastic wire. This, when referred to its modulus of rigidity and length, gave the couple acting in the system. This enabled the stress in the test-piece to be calculated, the strain being obtainable by a pointer at the nether end of the test-piece moving over a circular scale. Thus a stress-strain diagram could be drawn and the stress at the limit of proportionality determined.

The actual machine was constructed as follows (Fig. 6): A flat perforated plate bent over at the sides was screwed on to wooden blocks bolted to the base of a heavy tall retort stand. Through this plate horizontally a cranked shaft was secured by collars and set-screws and carried a worm in the middle. Thrust through the middle of the plate was a vertical shaft with a worm-wheel on its lower extremity meshing with the aforesaid worm,

and secured to the vertical shaft by a set-screw. Above the plate a pointer was secured between two collars and set-screws, and moved over a protractor scale graduated in degrees, bolted to the plate. A 5-inch piece of $\frac{1}{2}$ inch diameter mild steel had a



TORSION MACHINE FOR WIRES AT HIGH TEMPERATURES

FIG. 6.

$\frac{3}{16}$ -inch hole drilled into one extremity for 2 inches. This was slipped over the remainder of the vertical shaft and secured thereto by a $\frac{3}{16}$ -inch set-screw. At the other end of this cylinder a $\frac{3}{16}$ -inch hole was drilled $\frac{1}{2}$ inch deep, and a $\frac{3}{16}$ -inch set-screw was fitted into it. To act as grips a $\frac{1}{8}$ -inch split pin was sawn in two so as to yield two semi-cylinders $\frac{5}{8}$ inch long. These had

a small groove filed along the flats to locate the wire test-piece which was slipped between them, the whole assembly placed in the upper hole and screwed up tightly with the set-screw. A $2\frac{1}{2}$ -inch piece of $\frac{1}{2}$ -inch mild steel was drilled with a $\frac{3}{16}$ -inch hole, $\frac{5}{8}$ inch deep at either end, with $\frac{3}{16}$ -inch set-screws as before. In one of these a similar pair of grips was placed so as to secure the upper end of the test-piece; the other hole secured the lower end of the elastic weigh-bar. A galvanometer mirror was stuck on to a sliding mounting, consisting of a collar and set-screw, which was slipped on to the weigh-bar, the upper extremity of which was clamped to the retort stand.

All the holes drilled as above were made slightly eccentric so that the tightening of the set-screws brought the wire or shaft to the centre line of the assembly.

An electric furnace 13 inches long, $1\frac{1}{4}$ inch diameter, was wound with nichrome wire, and placed round the test-piece. The bottom cylinder projected about 2 to $2\frac{1}{2}$ inches into the furnace, as a test-piece with an effective length of 9 inches between grips was used. The top end of the test-piece was just within the furnace. This expedient was taken so that it was impossible for the top portion to touch the furnace by virtue of any misalignment of the latter. Exploration of the furnace showed that the heating was very uniform up to about 250° C., and that it was quite tolerably uniform up to about 400° C., when about 8° C. was the maximum variation from the temperature in the middle by the same thermocouple and outfit as was used for the resistivity work. The top and bottom orifices of the furnace were closed by asbestos.

The modulus of rigidity of the weigh-bar was determined by suspending a rectangular bar from the end and counting the time of one torsional oscillation; the moment of inertia of the bar and the dimensions of the wire being readily found, the modulus could be calculated, and as the mean of two concordant results was found to be 5604 tons per square inch.

The deflection of the weigh-bar was read by reflecting the image of a spot of light with a hair line on to a galvanometer scale 1 metre away from the mirror. The deflection could be varied by sliding the mirror up and down the weigh-bar. It was so adjusted that the average limit of elasticity was equivalent

to a deflection of about 15 to 20 centimetres, readings to 0.25 millimetre being easily possible.

A standard test-piece was used so as to render all results directly comparable. A calibration curve was prepared trigonometrically to enable centimetres of deflection to be converted directly into radians of twist of the weigh-bar.

Experiments were carried out to determine the effect of varying the tension throughout the system. This within normal limits was negligible, as was to be expected.

It was found desirable to fit a support half-way up the weigh-bar to damp out any vibrations. The top of the retort stand was clamped to a rigid bracket on the wall, for the same reason. A plumb-line was used to check the vertical alignment of the system. A uniform test-piece of 9 inches length between grips was used in all cases. The high carbon steel B wire used in the experiments was 0.0195 inch in diameter, and the electrolytic iron wire C was 0.026 inch in diameter. The method of taking a curve was as follows : A test-piece was fixed in the grips, which were detached for the purpose ; the upper grip was secured to the weigh-bar and the lower one was slipped over the torsional shaft at the bottom, and the set-screw tightened. By elevating the top clamp of the weigh-bar a tension just sufficient to tauten the whole assembly was placed on the system. The furnace was adjusted so as to leave a clear annular space around the grips, and the openings closed by asbestos. The furnace was then brought to the desired temperature and kept there for half an hour. The spot of light was then so adjusted as to be on the left half of the scale and its position read. Successive equal amounts of twist, in the case of the high carbon steel, 10° , and of the electrolytic iron, 5° , were imposed at the lower end by the torsion gear, and the deflection of the spot of light noted after each. This was continued until the limit of elasticity was obviously passed. It was found advisable to discard the first reading, which was usually low, owing to the taking up of slack in the system. Also the time intervals between each increment of strain were kept constant. It would have been logical to have read the strain after equal increments of stress, but this was impossible, owing to the screen being a metre away from the torsion gear. A stress-strain diagram could then be drawn up

having as ordinates stress expressed as deflection of weigh-bar corrected to radians, and as abscissæ strain expressed as degrees of twist of the lower end of the system.

The limit of proportionality was determined by running a straight edge along the curve and noting the first deviation from a straight line.

Curves were taken on both the high carbon steel B and the electrolytic iron C, at intervals of 20° C. from room temperature of 30° C. up to 370° C. for B and 410° C. for C. Shortage of material prevented any work being done on the mild steel A.

The stress-strain curves for B and C are shown in Figs. 7 and 8 respectively, and the curves showing variation of elastic limit with temperature in Figs. 9 and 10.

Duplicates were done at many of the points, and were always within 1 per cent. of the originals. Oxidation even at 400° C. was absolutely negligible. The curves themselves are very striking in shape and are very similar.

In the electrolytic iron figures there are well marked maxima or minima at 80° C., 120° C., 170° C., 230° C., 270° C., 310° C., 370° C., with a slight irregularity at 390° C., all of which correspond with some peak in the resistivity curves (Fig. 4).

The minimum at 120° C. corresponds to a peculiar stress-strain curve (Fig. 8), which was repeated three times, always with the same result.

The high carbon steel (Figs. 7 and 10) gave minima and maxima at 50° C., 90° C., 120° C., 170° C., swallowed up in a big point at 190° C., 230° C., a slight irregularity at 250° C., 270° C., 320° C., with indications of a minimum at 390° C., all of which correspond with something on the resistivity curves (Fig. 3).

Hence it appears that, contrary to Robin's dictum, the elastic limit is a very sensitive indicator of transformations in the solid.

From an engineering point of view the minimum at 120° C. and maximum at 190° C. are particularly worthy of note. These strange maxima and minima must be authentic, as (1) they are not isolated points, but points which lie on smooth curves leading to and away from them; (2) duplicate tests have checked to within 1 per cent.; (3) the curves for B and C (Figs. 9 and 10) are so strikingly similar.

It is interesting to observe that a low value of the elastic limit is as a rule associated with a high modulus of rigidity indicated by an increase of the angle that the elastic portion of the curve makes with the horizontal (Figs. 7 and 8).

Consideration of the discontinuities observed in both the resistance and elastic limit experiment indicates that changes

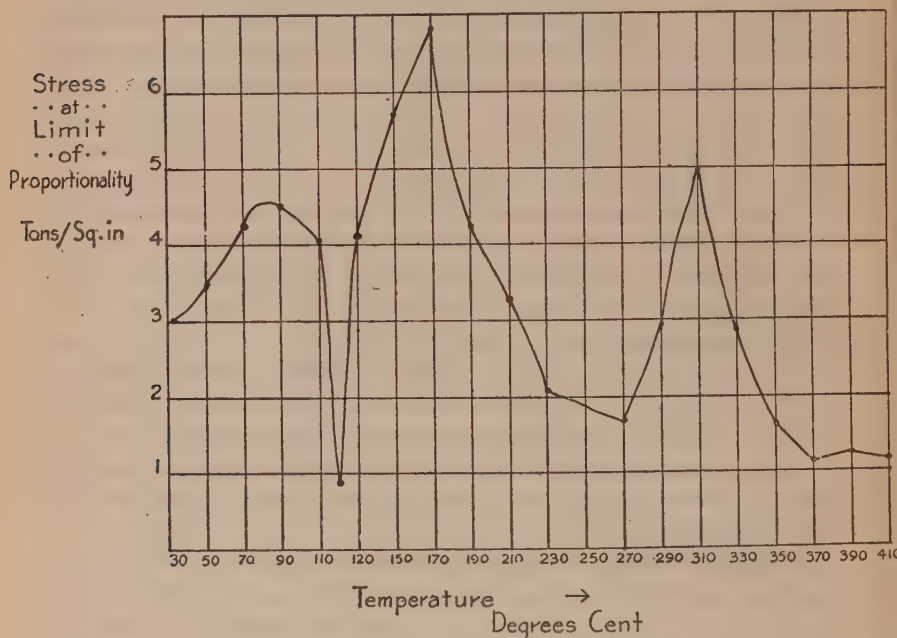


FIG. 9.

at the following temperatures occur in all the materials : 70° C., 120° C., 170° C., 230° C., 290° C., 310° C., 350° C., and also at the following temperatures in the case of the steels, 90° C., 190° C., with a suspicion of a point at 160° C. and 250° C. It may therefore be said that the first group of points is due to the iron, while the second is due to the iron carbide.

It is noticeable that all the iron points are depressed considerably by the presence of carbide, 0.99 per cent. carbon depressing them about 20° C.; the hysteresis between heating and cooling also increased (see Figs. 2, 3, and 4).

The high carbon steel B, with 0.99 per cent. carbon, equivalent to about 15 per cent. iron carbide, gave somewhat confused curves, owing to the carbide changes masking the iron points. This was not nearly so pronounced in the mild steel A.

The elastic limit determinations (Figs. 7, 8, 9, and 10) are the most interesting portions of the work, and reveal the extra-

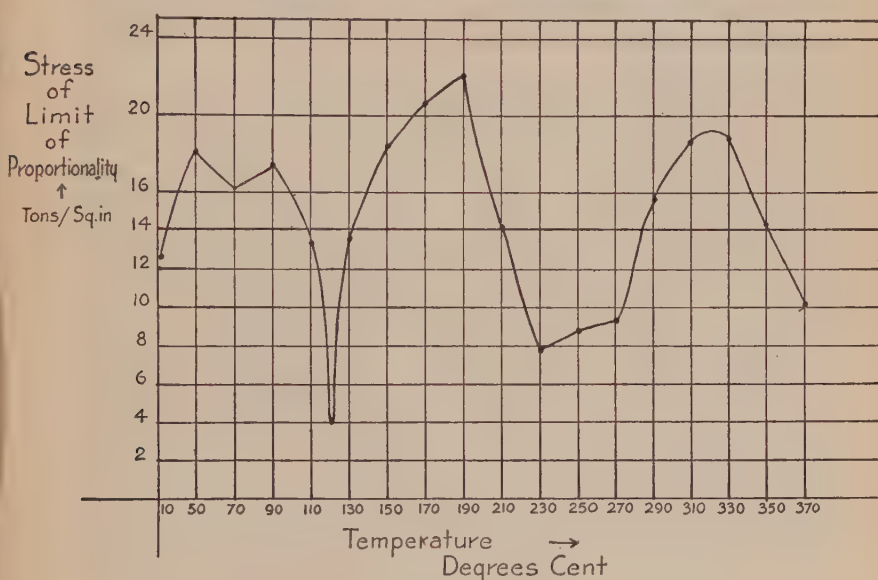


FIG. 10.

ordinary sensibility of this property to changes in the solid. The remarkable minimum at 120° C. is worthy of note in connection with heat engines, many of whose parts are working at or about this temperature. The rapid return of elasticity 10° C. higher is also very strange.

Although it is yet early to generalise, some attempts have been made to explain these results, and will be described below.

Allotropy, in the sense of a change of the space lattice, is discounted by the number and small size of the discontinuities. To expect five or six allotropic changes in a range of 350° C. with possibly at least as many at higher temperatures, as is indicated

by Borelius and Gunneson, is manifestly absurd. In addition, the work of Westgren and Phragmén⁽²⁶⁾ shows that no such changes have been observed by them. The fact that these changes have been observed in vacuum-melted electrolytic iron by Borelius and Gunneson, and in vacuum-annealed electrolytic iron by the present authors, disposes of the contention that they are due to dissolved gases or other impurities. Further, the fact that these changes occur also on cooling is incomparable with a gas theory.

It has been suggested that unstable conditions may obtain between adjacent crystal grains which may, on heating up the metal, be relieved, and thus cause minor discontinuities in the physical properties. However, these points are observed at similar temperatures on cooling and also on subsequent reheatings, by which time all such instability would be expected to have disappeared. Further, no grain growth has ever been observed in iron at the temperatures of the lower changes.

Having, therefore, no reason to believe that the crystals, as such, or the atomic arrangement within them, are altered, by a process of elimination, we are driven to seek the explanation of these phenomena within the atom itself. It is felt that these changes are the result of alterations in the arrangement, or movement, of the electrons around the positive nucleus of the atom. This arrangement is closely connected with the characteristic vibration frequency of the atom. Bohr's theory of atomic constitution cannot as yet tell us the exact arrangement of the electrons in the iron atom, as there are several alternative arrangements which cannot be discriminated. Iron of atomic number 26 occurs in the group between scandium, atomic number 21, and nickel, atomic number 28, in which the outer electrons, instead of forming 4 quanta orbits in continuity with the structure of calcium, atomic number 19, divide into 3 quanta orbits. This would appear to indicate that some of these elements would tend to have alternative structures available. Again, iron has very strong magnetic properties, which Bohr holds to be due to a very unsymmetrical arrangement of the electrons. Now, at 760° C. an A2 point iron loses nearly all these magnetic properties, while the only other physical property undergoing any drastic abnormality is the specific heat. According to

Bohr's theory, one would expect an alteration in the atomic structure to a more symmetrical form, which would also be reflected in a change in the specific heat, this being a property closely related to the atomic structure of crystalline matter in general. If this change in the structure were very great there would assuredly be parallel and far-reaching changes in all of the other physical properties, which is contrary to what actually happens. The authors would submit that these low temperature changes which they and others have observed correspond, on heating, to changes in the atomic structure tending to a more symmetrical arrangement which culminates in the A2 point at 760° C., thus damping down the violence of the latter change. It is worthy of note that the magnetic properties by no means cease entirely at the A2 point, and that Borelius and Gunneson have observed these changes at temperatures up to more than 900° C., also that Honda^(15 and 16) and others have observed small magnetic changes in iron at low temperatures. The reverse changes are regarded as taking place on cooling.

Discontinuities in the rate of increase of specific heat at constant pressure of very low carbon steels have been observed among the results obtained by the following workers : At 300° C. by Harker,⁽²⁰⁾ at 320° C. by Oberhoffer,⁽²¹⁾ at 300° C. by Pionchon,⁽²²⁾ and at 200° C., 250° C., and 300° C. by Stucker,⁽²¹⁾ all of which temperatures correspond to some of the discontinuities under discussion.

Now, the specific heat at constant pressure is related to that at constant volume, according to the expression :

$$C_p = C_v \left(1 + 9 \frac{T\alpha^2 V}{K C_v} \right)$$

where C_p = specific heat at constant pressure ;
 C_v = " " " " volume ;
 T = absolute temperature ;
 V = molecular or atomic volume ;
 K = compressibility ;
 α = linear coefficient of expansion.

Any discontinuous variations in α , V , or K are negligible, as they only occur in a small correction term.

Einstein gives us an expression connecting the atomic frequency with the specific heat at constant volume at any temperature for a monatomic solid :

$$C = 3Nk \frac{x^2 \cdot e^x}{(e^x - 1)^2} \text{ where } x = \frac{h\nu}{kT}$$

- C = specific heat at constant volume ;
 N = number of atoms in 1 gramme-atom ;
 h and k = fundamental constants ;
 ν = atomic frequency of vibration ;
 T = absolute temperature.

This expression, when differentiated with respect to C and T , gives us the rate of increase of C with varying T . If this rate in itself varies discontinuously, then any or all of h , N , k or ν must vary.

Of these, N is a function of the atomic weight alone and so is invariable, and h and k are fundamental constants ; hence ν must vary at these discontinuities.

The form of the expression is such that a decrease in ν necessitates an increase in C . A similar result is obtainable from the Nernst-Lindeman modification of Einstein's formula.

Debye, postulating a range of frequencies for a given atom, with a characteristic maximum value ν_m , deduces an expression giving a similar result for this maximum frequency. He also obtains an expression for the maximum frequency in terms of the elastic moduli of rigidity and bulk, such that an increase in the frequency implies a decrease in the moduli.

It is more difficult to treat of the discontinuities in the electrical conductivity along these lines, as there is as yet no satisfactory theory of metallic conduction.

Borelius ⁽²³⁾ derives the following expression for the electrical conductivity of a metal :

$$\chi = \frac{1}{2} \frac{\epsilon^2 \nu}{r u}$$

- where χ = conductivity ;
 ϵ = electronic charge ;
 ν = atomic frequency ;
 r = atomic radius ;
 u = mean energy of electron
 = $C T$,
 when C = constant,
 T = absolute temperature.

In the expression also, a fall in ν will mean a decrease in electrical conductivity, *i.e.* a rise in resistivity.

To particularise the above generalisations : a decrease in the frequency of vibration of the iron atom at 300° C. or

thereabouts, according to the above reasoning, should bring about :

- (1) An abrupt rise in electrical resistance.
- (2) A fall in the bulk and rigidity moduli.
- (3) An abrupt rise in specific heat at constant volume.

All these have been observed either by previous workers or in the present work. Direct determinations of the bulk modulus have not been made, but its value can be calculated from Young's modulus and the rigidity modulus.

To return to the consideration of the discontinuities we have observed in the physical properties of iron, we may be said to have established a chain of evidence connecting the observed phenomena with changes in the arrangement of the electrons of the iron atom. It is therefore suggested, as an explanation of those remarkable discontinuities, that they are due to rearrangement of the electronic structures.

As far as is known this conception is entirely new, and further speculation is unwarranted until more experimental data is obtained.

SUMMARY.

1. Contemporary literature has been shown to afford evidence of abnormalities in the behaviour of iron and steel at temperatures below the carbon-change point.

2. Measurements of electrical resistivity and torsional elastic limit have shown the existence of a number of change points at 70° C., 120° C., 170° C., 230° C., 290° C., 310° C., and 350° C., small in the electrical resistivity, but very striking in the elastic properties, in low and high carbon steels and in electrolytic iron.

3. A theory has been deduced to explain these changes as due to alterations in the structure of the iron atom.

In conclusion, the authors would like to express their thanks to Mr. H. W. Baker, Lecturer in Engineering in the University of Manchester, for his help in the design of the torsional testing machine.

The whole of the work has been carried out with the aid of a grant from the Department of Scientific and Industrial Research, to whom the authors take this opportunity of expressing their thanks.

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CORRESPONDENCE.

Dr. R. H. GREAVES (Woolwich) wrote that he desired to congratulate the authors on the striking additional evidence they had obtained of discontinuities in the temperature coefficient of resistance of iron and steel. The evidence of variations of the magnitude suggested in the elastic properties did not seem to him to be so convincing. The authors' interpretation of the results on electrolytic iron at 120° C. (Fig. 8) was, he thought, quite unprecedented. Apart from experimental error in the initial readings, he only remembered stress-strain diagrams of the form indicated in cases in which relief of internal stress was proceeding at the same time as straining, and so vitiating the results. Results of mechanical tests at elevated temperatures were difficult to interpret on account of the effect of strain-hardening. The effect of rate of straining was very pronounced in determining departure from proportionality, and the effects of a given rate of straining were different at different temperatures. It appeared to him that the authors' results would have to be supplemented and very critically considered before the exact temperature and magnitude of changes in elastic properties could be decided.

The explanation advanced by the authors embodied a most interesting speculation. In this connection he might point out that, in addition to the discontinuities in specific heat referred to on p. 485, a marked departure from the smooth parabolic relation of specific heat and temperature was found by E. H. Griffiths and E. Griffiths at 66° C.¹ The spacing of their points was too open to decide where the maximum discrepancy occurred, but it might have some relation to the 70° C. change point observed by the authors.

The value of ν_m obtained from Griffiths' smooth atomic heat curves over a low temperature (liquid air) range agreed very closely with the values deduced by Debye from the elastic constants of the metals in every case except iron, which gave : ²

$$\nu_m \text{ (atomic heat), } 8.0 \times 10^{-12} ; \nu_m \text{ (elastic constants), } 9.7 \times 10^{-12}.$$

This divergence indicated an anomaly in iron which did not occur in the case of Cu, Al, Ag, Cd, or Pb, and which affected either the elastic constants or the specific heat of iron, but not both to the same relative extent. It was natural to associate the divergence in the case of iron with its magnetic properties. It seemed pretty well established that the ferro-magnetic properties of the iron atom were due to an inner system of electrons, while an outer shell was responsible for cohesion.

¹ *Philosophical Transactions, A.*, vol. cexiii. p. 172.

² *Ibid.*, A., vol. ccxiv. p. 348.

Changes in either system would affect the specific heat, but the magnetic changes need not, and in fact did not, greatly influence the elastic constants. The relation of the points observed by the authors to the intensity of magnetisation of the specimen might possibly throw some light on their origin.¹

The AUTHORS, in a written reply, welcomed Dr. Greaves' very interesting contribution, the more so that it offered some confirmation of their conclusions as to the cause of the changes in iron which they had propounded. They were also grateful for the references given. With regard to the low elastic limit found at 120° C., they were absolutely convinced that the low elastic limit at that temperature was as reported in the paper. Four curves were obtained at the temperature, since they were quite alive to the remarkable nature of the result. Further, as they stated in the paper, it was only if an almost non-elastic condition of affairs obtained that Robin's "aphonia" could be explained. It, of course, might well be, as Dr. Greaves pointed out, that at 120° C. something akin to strain hardening or relief of strain occurred since the change from one form of iron to another was just the condition under which such would be expected to occur. In a material just on the borderland between two different stable states markedly abnormal elastic limits would be far from surprising.

¹ Cf. A. Gray and E. Taylor-Jones, "Change of Resistance in Iron by Magnetisation," *Proceedings of the Royal Society*, 1900, vol. lxvii. p. 208.

Iron and Steel Institute.

A NOTE ON TEMPER-CARBON.

By L. NORTHCOTT, B.Sc. (UNIVERSITY OF BIRMINGHAM).

CONSIDERABLE attention has been directed to the nature of the elementary carbon which occurs in cast iron. Ledebur¹ gave the name "temper-carbon," meaning annealing carbon, to that form of carbon obtained during the annealing of white pig iron, and states that temper-carbon differs from graphite by its amorphous condition. Bauerman,¹ in the discussion of Ledebur's paper, stated that both varieties were equally good graphite, alike in physical and chemical properties. The Committee, appointed by this Institute, on The Nomenclature of Metallography, in 1902 defined temper-carbon as "The apparently amorphous, finely divided carbon having some graphitic properties."²

Whether the finely divided carbon which separates during the annealing of white iron is merely finely divided graphite, or whether it is some special and distinct form of carbon to which the term amorphous might be applied, is the question to be considered. For the purpose of this inquiry, a sample of temper-carbon was prepared and compared with natural graphite and with specially prepared amorphous carbon. The sample of temper-carbon was prepared from malleable cast iron of good quality, by the method described in Professor Turner's "Lectures on Iron Founding" (2nd edit.), p. 55. The iron used had the following composition :

Carbon per Cent.	Silicon per Cent.	Phosphorus per Cent.	Sulphur per Cent.	Manganese per Cent.
2·4	0·5	0·02	0·038	0·02

The iron was dissolved in concentrated hydrochloric acid, the carbon and siliceous residue washed well with water, and then digested with a very strong solution of caustic potash. The solution was filtered, washed with strong hydrochloric acid to remove last traces of iron, and the filter dried. The graphite residue was digested with hydrofluoric acid, and was strongly

¹ *Journal of the Iron and Steel Institute*, 1893, No. II. p. 57.

² *Ibid.*, 1902, No. I. p. 95.

heated in order to drive off any silicon fluoride fumes. The digestion with hydrofluoric acid was repeated twice and the carbon dried. The amorphous carbon intended to be used for comparison was prepared by burning acetylene gas at low pressure and collecting the lampblack given off by the incomplete combustion of the gas. Both the graphite and lampblack were treated with hydrofluoric and hydrochloric acids and finally dried in a muffle at a temperature of 250° C.

1. MICROSCOPICAL EXAMINATION.

No definite conclusions could be drawn from microscopical evidence, since higher magnifications than $\times 50$ could not be used in complete focus. The lampblack was distinctly blacker, as regards colour, than the other two samples. It must be remembered that the essential difference between crystalline and amorphous substances is one of internal structure, and not necessarily of external shape.

2. DENSITY.

When endeavouring to obtain the density by weighing in water, considerable difficulty was experienced in thoroughly wetting the powders. This applied more particularly to the graphite. The presence of minute air bubbles due to incomplete wetting of the substance would naturally lower the apparent density considerably. The specific gravity bottle method was employed, and good results were obtained by the use of methylated spirit in the place of water. The maximum densities obtained were as follows :

Density	Lampblack.	Graphite.	Temper-Carbon.
	1.5	2.33	2.48

It will be seen that the density of temper-carbon lies well within the graphite range, and that it is considerably higher than that of amorphous carbon.

3. IGNITION TEMPERATURES.

A gas-heated silica-tube furnace was employed for these determinations. Atmospheric air, previously passed through

caustic soda solution, was passed through the tube at a constant rate of 1 litre per two and a half minutes. The temperature was indicated by a base metal thermocouple. The air was led from the tube furnace by bent glass tubing into a clear solution of lime-water. The first definite appearance of milkiness in this liquid denoted the presence of carbon dioxide in the gas. The ignition temperatures observed were as follows :

Ignition temperature	Lampblack. 550°	Graphite. 670°	Temper-Carbon. 650°
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It will be seen that the temper-carbon has an ignition point much nearer that of graphite than that of amorphous carbon. The ignition point of finely divided graphite might be expected to be somewhat lower than that of the same substance in larger particles.

4. FORMATION OF GRAPHITIC ACID.¹

The action of nitric acid on graphite is characteristic and distinguishes graphite from amorphous carbon. The graphitic acid is obtained by the action of chlorate of potash and very strong nitric acid on the graphite, the action being repeated several times in succession. The experiment was tried with a sample of temper-carbon, and after the third time of oxidation with the nitric acid and chlorate of potash there was a distinct change, the black colour of the carbon absolutely disappearing, leaving an almost colourless liquid which, on further warming and drying, left a white or very pale yellow mass at the bottom of the flask.

Although a microscopical examination does not distinguish between amorphous carbon and finely divided graphite, the fact that temper-carbon yields graphitic acid, and that its density and igniting point agree with those of graphite while it exhibits a definite crystalline character, appear to place beyond doubt the fact that temper-carbon or secondary graphite is not amorphous carbon, but that it possesses all ordinary properties of graphite and is merely that material in a state of fine division. In other words, when iron is cast there are not two actions, one of which leads to the formation of graphite, and the other, at lower

¹ C. Brodie, *Philosophical Transactions*, 1859, p. 249.

temperatures, leads to the formation of a special form of carbon, but one continuous action leading to the deposition of graphite, the only difference being that this graphite is more finely divided, owing to the metal being more rigid as the temperature falls. Attention might be drawn to a paper recently published by Kei Iokibe,¹ who compared natural graphite, temper-carbon, and sugar-carbon, and on examination by X-rays showed that the amorphous carbon was non-crystalline, while the other carbons had a structure of a crystalline character.

In conclusion, the author wishes to express his thanks to Professor T. Turner for suggestions and advice during the course of this work.

¹ Tôhoku University, *Science Reports*, No. ix.

CORRESPONDENCE.

Sir ROBERT HADFIELD, Bart., F.R.S., Past-President, wrote referring to a paper he had read before the Iron and Steel Institute in 1894 on "The Results of Heat-Treatment on Manganese Steel and their Bearing upon Carbon Steel." In that paper he drew attention to the fact that certain changes were produced in malleable iron by heat-treatment (see table on next page.)

At that time there was some controversy as to whether the carbon present was really graphitic or, as claimed by Ledebur, another form of carbon which was termed temper-carbon. However, as the result of his experiments it was clearly proved that temper-carbon and graphite were practically the same, the former being merely in a more finely divided condition than in the ordinary graphitic formation.

The same material when forged could be made to acquire no less than 0.53 to 0.70 per cent. of combined carbon—that was to say, such forged material when quenched gave glass-scratching hardness; in fact, a small turning tool was forged and used with quite satisfactory results. As it was shown, temper-carbon could be turned into combined carbon without it being necessary to remelt the product.

Another singular point noticed in those experiments which seemed to him of particular interest at the time, and indeed was still so, was the fact that there was little decarburisation effected, that was to say the carbon merely transferred its form into graphitic temper-carbon or vice versa.

The idea which was at one time current, that the malleablising of cast iron was effected by entire decarburisation, was not, of course, correct.

There was an interesting discussion on the paper referred to, in which the authorities of those times joined, for example, Dr. Stead, Sir William Roberts-Austen, Mr. P. C. Gilchrist, Dr. John Hopkinson, Mr. André Le Chatelier, Professor H. Le Chatelier, Professor Ledebur, Louis, Wedding, Harbord, Fleming, Müller, Arnold, and many others.

Mr. NORTHCOTT, in replying to the written discussion on his paper, desired to thank Sir Robert Hadfield for calling attention to a paper which, on account of its title, had escaped notice when searching the literature. It was interesting to find that Sir R. Hadfield's observations on carbon steel were in accord with the conclusions arrived at by the author from a study of malleable and grey cast iron, and that questions which at one time were apparently in doubt might now be regarded as definitely settled.

TABLE I.

No. of Specimen.	Whether subse- quently Forged.	Tested in Cast or subse- quently Forged Condition.	Nature of Treatment.	Tempera- ture at which Water Quenched.	Specific Gravity.	Combined Carbon by Ordinary Colour Test (Eggertz).	Graphite or Graphitic Temper- Carbon. ²	Percentage of the Two Forms of Carbon added together.	Total Carbon by Com- bustion. ³	Total Carbon in Original Sample.	Carbon unac- counted for by Ordinary Analysis.	Remarks.
1	No	Cast	None. Tested in original condition	...	7.28	trace	3.07	= 3.07	3.07	3.07	...	This represents the sample in the original state.
2	No	Cast	Hardened	920° C.	7.16 ¹	0.83	1.74	= 2.57	2.55	3.07	0.52	
3	Yes	Forged	Heated to 920° C. and cooled in air	...	7.23	0.53	2.24	= 2.77	2.73	3.07	0.34	
4	Yes	Forged	Hardened	920° C.	7.38	0.70	1.64	= 2.34	2.23	3.07	0.84	

Analysis of original sample . . . C. trace Gr. 3.07⁴ Si. 0.23 S. 0.04 P. 0.20 Mn. 0.26 per cent.

¹ This being so low, it was repeated; the second determination showed 7.15 specific gravity.

² Iron dissolved in nitro-hydrochloric acid. Silica separated by soda, washed, and graphite burnt off.

³ By cupro-ammonium-chloride method.

⁴ The specific gravity of the graphite or temper-carbon separate was 2.25. It was entirely non-magnetic, showing that it had been thoroughly separated from any iron originally present.

Iron and Steel Institute.

THE POTENTIAL ENERGY OF COLD-
WORKED STEEL.

By THOMAS F. RUSSELL, ASSOC.MET. (SHEFFIELD).

“We say that we have ‘explained’ a physical or chemical phenomenon when we can restate it in terms of mechanics, that is, when we can show the phenomenon in question is to be anticipated on the basis of a number of principles logically applied.”—McLEWIS.

IN a paper published in the *Journal of the Iron and Steel Institute*, 1921, No. I., entitled “A Note on the Ball Test,” by Baker and Russell, it was shown that the ordinary tensile testing machine may be used to determine a fundamental mechanical property of a metal, which the authors called the “specific work of rupture.” This is the figure which would be obtained in the following purely hypothetical case. Suppose a unit volume of steel be subjected to a tensile load until fracture occurs, and that the change in shape be brought about whilst the sides remain parallel throughout, then the work done in these circumstances is the specific work of rupture (Fig. 1). It is readily obtained from a work diagram by plotting the load against the extension *e*, as explained fully in the original paper.

The object of the present paper is to discuss certain features, which, as far as the author is aware, have not been dealt with elsewhere. Very few of the conclusions are given with finality—far too little work has been done for that—and although some of them are convincing, others must be taken as suggestions or possibilities to be proved or disproved by further experiments.

The steel used had the following percentage composition :

	Per Cent.
Carbon	0·06
Silicon	nil
Manganese	0·34
Sulphur	0·026
Phosphorus	0·015

The heat treatment and the ordinary or commercial mechanical properties are shown in Table I. The heat treatment was such that two series ACE and BDF of increasing grain size might be

anticipated as occurring. As a matter of fact, these two series dovetailed very well, so that there is one continuous series

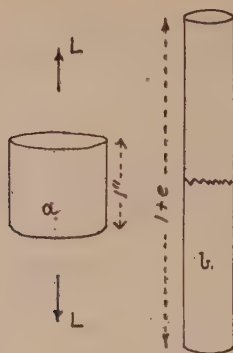


FIG. 1.

ABCDEF of gradually increasing grain-size, and it is interesting to observe the gradual decrease of the yield point. This is referred

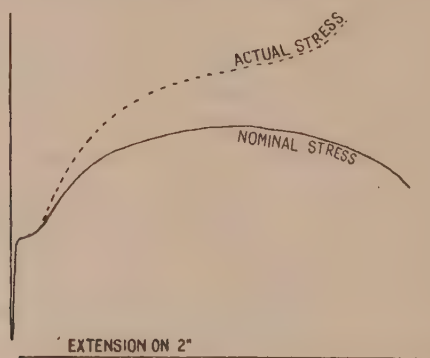


FIG. 2.

to later. The photomicrographs of steels A and F are shown in Plate XIX.

The ordinary load-extension diagrams are all of the type shown by the continuous line in Fig. 2—that is, there is a distinct step at the yield point, and, as is usual in these cases, the line of proportionality reaches within 1 to 2 tons of the yield point.

The dotted line shows what is often called the "actual stress"-strain diagram, obtained by plotting the actual stress against the elongation of an arbitrarily chosen length of 2 inches. The empirical nature of the tensile test—as far as the so-called maximum stress, elongation, and work diagram are concerned—is generally recognised, but whereas these three items have great commercial importance, the author ventures to suggest that the "actual stress"-strain curve, as exemplified by the dotted line in Fig. 2, has no value whatever.

Much more valuable, as indicating the true properties of the

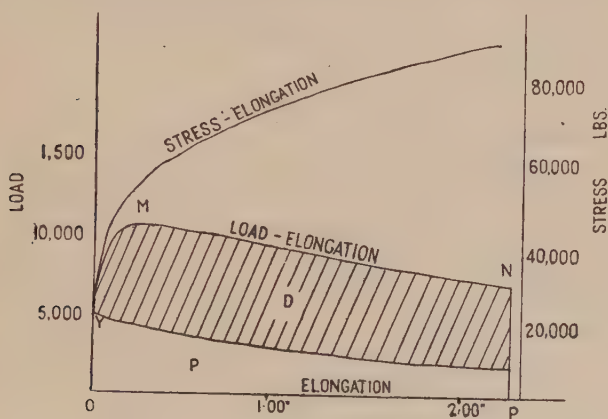


FIG. 3.

steel, are the fundamental load-extension and fundamental stress-extension curves shown on pp. 351 and 352 of the original paper. These curves have been replotted for steel F from the data given in Table II., and are shown in Fig. 3. The area YMNPO is a measure of the amount of work to rupture unit volume.

Before attempting to discuss what becomes of this work, it is well to recall, in the words of McLewis, the first law of thermodynamics :

" If, or whenever, heat is converted into work of any kind, or work into heat, there is always a definite quantitative relationship between the heat which has disappeared as such, and the work which has been done, or *vice versa*."

This is often stated in the form of the equation :

$$dQ = dA + dU,$$

which for the present purpose may be interpreted to mean that if a quantity of work dQ be done on a unit volume of steel, a portion of that work, dA , is used to bring about a change of volume, and the portion dU increases the internal energy of the steel. The separate quantities can now be considered in more detail.

The quantity dQ is obtained from the work diagram. The area is measured either with a planimeter or by counting the squares. In the example, the number of square millimetres is 20,745, and as 1 millimetre of the ordinate represents 100 lbs., 1 millimetre of the abscissa represents an extension of 0.01 inch, and the test-piece is 0.25 inch square in area.

Total work of rupture = $20,745 \times 100 \times 0.01 \times 4$ inch-pounds = 6915 foot-pounds.

The figures for the other steels have been similarly calculated, and are given in Table III. It should be noted how they gradually diminish as the series proceeds from A to F.

Steel has its density lowered by cold-working, and the quantity dA is a measure of the work done during the expansion of the steel against atmospheric pressure. Figures which show the density of normalised steel, and steel in its maximum state of cold-work as represented by the waist of a tensile test-piece, are not available, but an extreme value may be taken.

Specific gravity of normalised steel, 7.79.

Assume the specific gravity of cold-worked steel to be 7.5 (purposely exaggerated), atmospheric pressure 14.7 lbs. per square inch, and work per cubic inch = 0.05 foot-pound. The figure obtained is negligible when compared with the quantity dQ .

An apparently disturbing factor in the subsequent investigation of this subject is the effect of the elastic strain energy, or resilience, and its accompanying temperature change.

Now steel A, which has the highest yield point (taken as the elastic limit), has a maximum resilience of 1.98 foot-pound per cubic inch, and if no change in volume be assumed, this would cause a lowering in temperature of 0.07°C .—figures which may again be neglected when compared with the main figures dealt

with in the paper. These figures have been calculated merely to show that no great error is introduced if it be assumed that there is no change in volume in the cold-worked steel, and that the elastic strain energy can be neglected. The whole of the work expended on the steel goes, that is, to increase the internal energy, or $dQ = dU$.

If the internal energy of a body be increased, this energy may be either :

- (1) Kinetic, which would manifest itself as an increase in temperature ; or
- (2) Potential, which would be indicated by a change of phase.

It should be noted that if the whole of the work to rupture

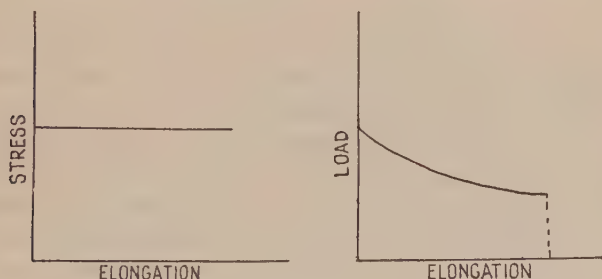


FIG. 4.

unit volume were converted into sensible heat, the temperature of steel A would be raised by no less than 213°C ., and steel F by 160°C ., but in practice the heat is conducted away so rapidly that the rise of temperature is of the order of a few degrees only.

The author has attempted to estimate the increase in potential energy of cold-worked steel by comparing the properties of steel with those of a plastic body. By a plastic body is meant one which will flow under a constant stress. This stress must exceed a certain minimum. The theories of plasticity either imply or infer the presence of two phases, the solid and the liquid, although not necessarily two phases of the same component, and the stress required to bring about the change of shape is primarily a function of the quantity and viscosity of the liquid ; the viscosity, in turn, depending on the temperature.

In order to fix ideas, assume a unit volume of a substance, a , as in Fig. 1, to be composed of two phases, which can be called c and m , and to have a constant stress of flow σ . Now, if the shape be altered, at constant temperature, from a to b the stress-elongation and load-extension diagrams will be as shown in Fig. 4. The work expended is obtained from the work diagram (load-extension) or by calculation, thus :

$$\begin{aligned}\text{Yield point} &= \sigma \\ \text{Area} &= A = \frac{1}{1+e} \\ \text{Load} &= \sigma A = \frac{\sigma}{1+e} \\ \text{Work} &= \int \frac{\sigma}{1+e} de \\ &= \sigma \log_e (1+e)\end{aligned}$$

The whole of this work is converted into sensible heat, so that, as already stated, the above diagrams (Fig. 4) are only correct if the change be carried out isothermally.

If the work diagram for a plastic body be compared with that obtained for mild steel (bearing in mind that a plastic body is not hardened by cold-work, whereas steel is hardened), it is reasonable to assume that the hardening is brought about by the work D , that is, by the shaded area in Fig. 3. Further, it may be assumed that the rate of pulling of the test-piece is slow enough to allow the heat equivalent of the work P to escape by conduction.

The quantity of work P has been calculated from the yield point and the reduction of area, as already explained, and is given in Table III. The work D is taken by difference, and the first noticeable feature is the constancy of this value throughout the series. It seems to be fairly constant at 5000 foot-pounds per cubic inch, and this is commented upon later. This internal energy D may be either kinetic or potential. It cannot all be kinetic, otherwise the cold-worked steel would not be different in properties from the unworked; it cannot all be potential, as undoubtedly the test-piece gets warm.

It therefore becomes necessary to divide the work D into two portions. The kinetic energy would be lost by conduction, and the potential energy would be the cause of the hardening, for,

as is well known, cold-worked material is electro-positive to unworked—that is, it has a larger solution pressure due to the release of the extra potential energy. A question of extreme importance to the physicist is : “ What form does this increase in potential energy take ? ”

If the presence of a vitreous phase were generally accepted the answer would be simple, but as this is a controversial subject the author will endeavour to examine this theory, quite impartially, on a quantitative basis.

Consider, in the first place, the specimens of steel in the normalised or annealed condition. Table I. and the photo-micrographs merely confirm what is already well known, namely, that the yield point is dependent on the grain size, or, in other words, on the relative amounts of the crystallised material c and the material m between the crystals, whatever condition this material may be in. Further, an inspection of Fig. 3, and of every fundamental stress-elongation diagram, shows that the more work done on the steel (and hence the greater the potential energy) the higher the yield point becomes.

The only inference from these two statements is that m contains more potential energy than the crystalline material. This means that if m were to change to the crystalline state, at the same temperature, there would be an *evolution* of heat. Many metallurgists call this the “ amorphous ” condition, but do not admit its vitreous nature. It is interesting to note that Dr. Rosenhain writes : “ The amorphous condition is one in which the crystalline arrangement of the molecules is completely broken up, so that the molecules remain in a state of irregular arrangement similar to that which is supposed to exist in the liquid state. In fact, the ‘ amorphous phase ’ is regarded as being—from the point of view of the phase doctrine—identical with the liquid phase.” If this be so, what objection can exist to calling this a liquid phase ? Why hesitate to follow Beilby and say that this is a vitreous material ?

The writer can only conjecture that the probable answer to this question is that by every known law of physical chemistry it is demanded that before the liquid phase of iron can be formed the iron must have reached a minimum temperature of 1500°C. , and that hitherto the difficulty has been to explain satisfactorily

how such a temperature could be attained. The figures which are given in Table III. will be used to show that such a temperature is not only possible, but also very highly probable.

The work D, viz. 5000 foot-pounds per cubic inch, is equivalent to 12.71 calories per gramme. Now, Rosenhain and Ewing have shown that the distortion of a crystal takes place by a series of slippings over the cleavage planes. If this be accepted, the whole of the 12.71 calories must have been generated by friction on these cleavage planes, and it is quite feasible that a layer of perhaps a few atoms thickness may have been actually melted.

The vitreous theory may be explained diagrammatically as follows: The crystal *a* in Fig. 5 when subjected to a stress—taken as a shear stress for simplicity—would be strained, as shown by the dotted figure, and the temperature slightly lowered thereby.



FIG. 5.

When the stress reached a certain value there would be a slip along a plane *b*, and the friction would cause actual fusion of some of the metal—the temporary mobile layer. The elastic strain in the top and bottom portions would be relieved, and it would take time for them to become strained again, as in *c*. During this time the molten layer is chilled by the top and bottom portions of the crystal, the latent heat of formation is trapped, and the material remains in the vitreous condition. This view may be considered quantitatively:

Let x = the amount of iron which is raised to 1500° C., and then melted.

Then $Q_{1500} x + lx = 12.71$.

Where Q_{1500} is the quantity of heat required to raise the temperature of 1 gramme of iron from 0° C. to 1500° C., and

l is the latent heat of fusion of iron.

Q has been calculated from the determinations of the specific heats of iron at different temperatures made by P. Oberhoffer, and given in *Metallurgie*, 1907, and is found to be 226.6 calories. The latent heat of fusion of iron as determined by Wüst,¹

¹ *Die Temperatur-Wärmeinhaltsskurven der technisch wichtigen Metalle. Forschungsarbeiten, hrsgbn. vom Verein Deutscher Ingenieure No. 204. 1918.*

Meuthen, and Durrer is 49·35. These figures give a value of $x = 0\cdot046$. That is to say, for the particular mild steel under review, not more than 4·6 per cent. of the iron can be converted to the vitreous phase by cold-work, and the increase of potential energy is the equivalent of $\frac{49\cdot35}{275\cdot95} \times 12\cdot71 = 2\cdot27$ calories per gramme, or $9\cdot49 \times 10^7$ ergs.

These figures assume that the specific heat of the vitreous material is the same as that of the material in the crystalline state. The estimate of the quantity of the vitreous phase, and of the increase in potential energy, can only be approximate, as the gamma to alpha change has not been taken into consideration.

It will be noticed from Table III. and Fig. 3 that the presence of this 4·6 per cent. of vitreous phase has converted a steel whose mechanical properties were : Yield point, 9·25 tons per square inch ; maximum stress, 20·07 tons per square inch ; elongation on 2 inches, 48 per cent. ; and reduction of area, 68·83 per cent., into one with a yield point and maximum stress 43·3 tons and elongation and reduction nil. It is therefore submitted that this represents steel F in its maximum state of cold-work.

The constancy of the amount of work D at first suggests that this depends only on the composition of the steel. This, however, is not so. Figures so far examined seem to indicate that for any particular steel this quantity is a constant only when the steel is normalised from any temperature above the upper critical point, that is, it is quite independent of grain size. It decreases with increasing carbon content. For fully tempered steels, however, this figure is considerably increased for any one class of steel.

Work D is a measure of the capacity of a steel to be hardened by cold-work without intermediate heat treatment, and the observations in the last paragraph are entirely in agreement with works practice.

Estimation of the Order of Thickness of the "Vitreous Layer."

If the mode of formation of the vitreous layer be as described (Fig. 5), the thickness of the layer may be estimated in the following simple manner :

Steel A with an elastic limit of 16.9 tons has a proof resilience of approximately 2 foot-pounds per cubic inch.

5000 foot-pounds per cubic inch causes the formation of 4.6 per cent. by weight of the vitreous phase, or, neglecting the volume change, 4.6 per cent. by volume.

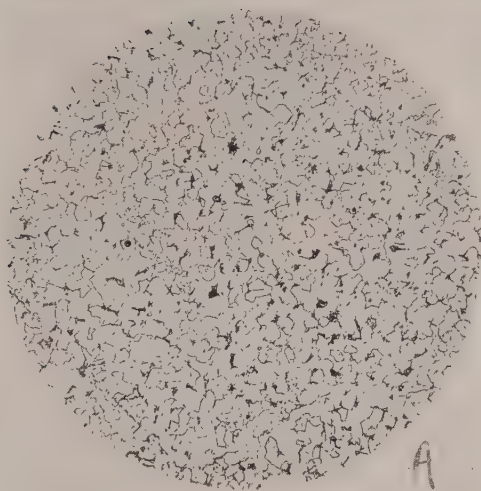
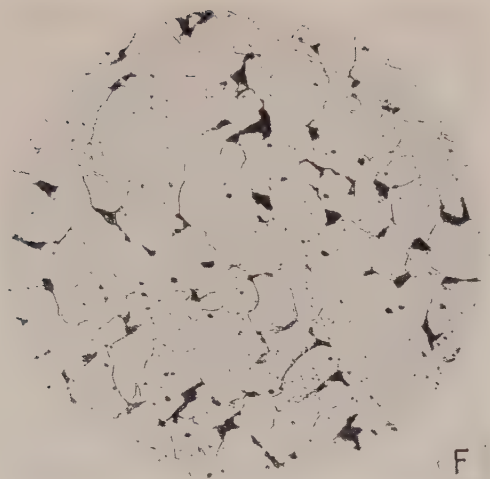
2 foot-pounds per cubic inch causes the formation of 0.00184 per cent. by volume.

Or, as the slip takes place over the full cross-sectional area, the thickness of the vitreous material is 0.00184 per cent. of the thickness of the crystal. If a typical grain be taken to be 1 millimetre thick, the thickness of the vitreous layer is 0.00000184 centimetre, or 184 Ångström units. Such a layer would not be visible under the highest power microscope.

This accounts, however, for only 2 out of 5000 foot-pounds. Now, Westgren and Phragmen have measured the length of the side of the body-centred cube, which is the space lattice of α -iron, and they found it to be 2.87×10^{-8} centimetres. This would indicate that a 1-millimetre cube of iron has $1/2.87 \times 10^{-7}$, say, 3,500,000 possible cleavage planes in each of the three principal directions. It is only necessary to conceive that in this drastically cold-worked steel slip has taken place on 833 of the planes, in each of the three directions, to have a complete answer to the question why *the vitreous phase is not visible under the microscope*. This estimation shows the fused layer to be $184/2.87$, or 64 atoms thick for an elastic limit of 16.9 tons, and the thickness would vary directly as the square of the elastic limit.

The Quantitative Measurement of the Increase in Potential Energy.

The truth, or otherwise, of the truly vitreous theory, as interpreted in this paper, can probably only be tested satisfactorily when actual measurements are made of the increase in potential energy of cold-worked steel, to see if it is of the order of magnitude found by thermo-dynamic reasoning. It has been stated repeatedly during the last twenty years that this increase of energy ought to be recoverable by calorimetric or electrolytic means, but, as far as the author is aware, no quantitative results have yet been published. Can it be that efforts to measure this energy have been made, but have given unsatisfactory or even negative



results? If such be the case, and if the author's estimate be correct, the explanation will be obvious—in any case, it is hoped that the following remarks will be of interest.

If the estimate of 2.27 calories per gramme of mild steel in its maximum state of cold-work is of the correct order, the increase in electromotive force due to this may be calculated. The electro-chemical equivalent will contain:

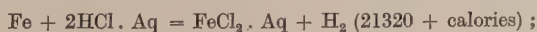
$$\begin{aligned} & 2.27 \times \frac{28}{108} \times 0.001118 \text{ calories} \\ & = 2.27 \times \frac{28}{108} \times 0.001118 \times 4.18 \times 10^7 \text{ ergs} \\ & = 0.000275 \times 10^8 \text{ C.G.S. units.} \end{aligned}$$

That is, the electromotive force generated when the cold-worked steel is one electrode and the unworked steel is the other, will be 0.000275 volt. Although this voltage can be measured comfortably with a good potentiometer, it is almost certain that a dynamic method would lead to fluctuations in the current of a much higher order than this. On the other hand, a static method would require an extremely sensitive capillary electrometer to measure satisfactorily such a small electromotive force.

As this 0.000275 volt is for iron in its maximum state of cold-work, it is interesting to compare this value with those obtained by Spring for some of the non-ferrous metals, and given in Desch's "Metallography," p. 287.

Sn in SnCl ₂	+ 0.00011 volt
Pb in Pb(NO ₃) ₂	+ 0.00012 „
Cd in CdCl ₂	+ 0.00020 „
Ag in AgNO ₃	+ 0.00098 „
Bi	exceptional.

That the electromotive force, as calculated from results obtained on a tensile test-piece, should give values of the same order of magnitude as the experimental determinations on other metals is remarkable, and in the author's opinion strongly supports the "truly vitreous" theory as set out in the early portion of the paper. A calorimetric method will probably be no more successful than the electrolytic method. The thermo-chemical equation for the solution of iron by hydrochloric acid is:



that is, 1 gramme of iron dissolved in HCl. Aq liberates 380.7

calories, so that the calorimeter used must be capable of measuring accurately 2.27 calories in 380.7. The practical difficulties would be very great, but would be diminished somewhat if a substance were formed whose heat of formation was lower than that of ferrous chloride. The direct union of iron with iodine suggests itself as being more likely to be satisfactory. But it is safe to prophesy that experimental methods must be much more refined before accurate determinations of the "state of cold-work" can be made either electrolytically or calorimetrically.

Amorphous and Vitreous.

The author has been quite unable to follow wherein lies the distinction that some metallurgists attempt to draw between the amorphous condition and the vitreous condition, and it may be as well at this stage to review the mechanism—as generally accepted—of the passage of a solid to a liquid and *vice versa*.

In a crystal the atoms are arranged in a definite order, and are held in their relative positions by the attractive forces between the atoms. Each atom, by virtue of its temperature, has a vibrational motion about its mean position. As the temperature of the mass is raised, the vibrational, or kinetic, energy of each atom is increased until, at a certain temperature known as the melting point, the vibrational forces overcome the attractive forces of the adjacent atoms. The atoms are now free to move; they are endowed with translational energy as well as vibrational energy. The attractive forces are still present, but continue to diminish with increasing temperature. The mass as a whole now has a new property, namely, viscosity—a property which was not possessed by the crystalline solid.

Viscosity is the property of a liquid or a gas, whereby it resists the relative motion of its parts. For each liquid the viscosity is a function of the temperature, and in every case it increases with fall of temperature.

Turning now to the reverse process, it is found that as the temperature of a liquid is lowered, the vibrational and translational energy of each atom is decreased, until, at a certain temperature known as the solidifying point, these forces are overcome by the atomic attractive forces and the atoms arrange

themselves in regular order. This must necessarily take time. If the rate of cooling be so rapid that, owing to the increased viscosity, the atoms are unable to arrange themselves in their crystalline order, there is no sharp passage from the liquid to the solid, and when the whole mass has cooled it is said to be in the "vitreous" condition and retains the essential property of a liquid, viz. viscosity.

The more complex the molecule, the more time will be required for crystallisation. The complex silicates, such as glass and slag, require an exceedingly slow rate of cooling to make them crystalline, but with a substance such as a metal, where all the atoms are similar, no known method of cooling is fast enough to keep even visible portions of the metal in the vitreous condition.

Now, the addition of heat to a mass of metal as a whole may be regarded as an extreme, or upper limiting case; the lower limiting case would be the heating of a single atom. Applying elementary principles, it is found that as the mass of an atom of iron is $56 \times 1.66 \times 10^{-24}$ grammes, the heat required to "fuse" this weight of iron is $56 \times 1.66 \times 10^{-24} \times 276$ calories, or in mechanical units, $56 \times 1.66 \times 10^{-24} \times 276 \times 4.18 \times 10^7$ ergs $= 1.073 \times 10^{-14}$ ergs. That is to say, the application, to one atom, of 1.073×10^{-14} ergs of work, either by rubbing, polishing, slipping over a gliding plane, or any other form of mechanical work, would be sufficient to "detach" it, as it were, from the main structure. At the moment detachment takes place, the atom would have the vibrational and translational energy required for 1500°C. , but both these would be instantly damped down to the values required for atmospheric temperature. In support of this view, it is interesting to note that Langmuir¹ estimates that, if the temperature of a surface layer be higher than that of the underlying ones, the time required to attain thermal equilibrium is of the order 10^{-16} seconds.

A large number of such atoms would constitute the "flowed layer," which is found when a metal is polished. This some metallurgists prefer to call the "amorphous" state. The essential condition that this amorphous state should be identical with the vitreous state is that there should be an evolution of the latent heat of solidification when the amorphous changes to the

¹ *Physical Review*, 1916, vol. viii. p. 149.

crystalline, at the same temperature, that is, the potential energy of the amorphous material must be higher than that of the crystalline material. This is known to be the case, and it only remains to measure this potential energy to establish the identity beyond any doubt.

In conclusion, this paper does not "prove" the presence of a vitreous phase, but is intended to show that the presence of a vitreous phase is "to be anticipated on the basis of a number of principles logically applied." The author is of opinion that if the presence of a vitreous phase be assumed, there is no phenomenon met with in mechanical testing that does not admit of a rational explanation.

The author's thanks are due to Messrs. Steel, Peech & Tozer, Ltd., and to Dr. T. Baker for kindly supplying the photomicrographs of the series of steels, and to Dr. F. Ibbotson of the Metallurgical Department of Sheffield University for the interest he has taken during the preparation of this paper.

TABLE I.

Steel	A.	B.	C.	D.	E.	F.
Treatment	940 ¹	940 ²	1040 ¹	1040 ²	1140 ¹	1140 ²
Yield point (tons per square inch)	16.91	15.07	13.23	12.48	11.95	9.25
Nominal maximum stress	21.93	21.39	21.45	20.83	20.08	20.07
Elongation per cent. on 2 inches	45.5	48.0	47.0	46.0	42.0	48.0
Reduction of area per cent.	74.1	75.0	73.2	72.12	70.2	68.83

¹ Cooled in air.

² Cooled in muffle.

TABLE II.

Tensile test data for steel F.
Original area, 0.25 square inch.

Load in pounds on section.
Stress in pounds per square inch.

Load.	Diameter.	Area.	Calculated Length on 100.	Stress.
5,180	Yield point	...	...	...
7,525	0.555	0.2419	103.35	31,108
8,670	0.550	0.2376	105.22	36,490
10,045	0.540	0.2290	109.17	43,863
10,730	0.530	0.2206	113.33	48,640
11,065	0.520	0.2124	117.70	52,095
11,210	0.510	0.2043	122.37	54,875
11,240	Maximum load	...	...	...
11,225	0.500	0.1964	127.29	57,153
11,180	0.490	0.1886	132.56	59,279
11,112	0.480	0.1810	138.12	61,388
11,000	0.470	0.1735	144.10	63,400
10,895	0.460	0.1662	150.42	65,554
10,720	0.450	0.1590	157.23	67,420
10,380	0.430	0.1452	172.18	71,487
9,965	0.410	0.1320	189.40	75,493
9,500	0.390	0.1195	209.20	79,496
8,975	0.370	0.1075	232.56	83,487
8,500	0.350	0.0962	259.87	88,356
7,915	0.330	0.0855	292.39	92,572
7,565	0.320	0.0804	310.94	94,092
...	0.315 broke	...	...	approx. 97,000

TABLE III.

All work expressed as foot-pounds per cubic inch.

	A.	B.	C.	D.	E.	F.
Work of rupture.	9199	8930	8097	8027	7760	6915
Change of shape. Assuming no						
hardening	4264	3920	3251	2974	2700	2014
Difference (D)	4935	5010	4846	5053	5060	4901

The " difference " approximately constant at 5000 foot-pounds per cubic inch
= 99 calories per cubic centimetre ; or 12.71 calories per gramme.

CORRESPONDENCE.

Mr. G. M. BROWN (Sheffield) wrote that in the joint "Note on the Ball Test," by Dr. Baker and Mr. Russell,¹ care was taken to avoid any definite pronouncement on the questions discussed, and simply stated that if there were no hardening effect due to cold work the quantity denoted by D in the present paper should represent the increase of the internal energy of the metal. They thus avoided two difficult points.

The work done on the test-piece was

$$\int P de,$$

where P was the applied load and e the extension, and the assumption that the whole of that work except the quantity

$$\int \frac{\sigma de}{1 + e},$$

where σ was the load at the elastic limit, was one which required some justification. This the author had not attempted.

The experiments of Hort² indicated that the amount of potential energy stored in that way was much smaller than the value of D given by the author, and is of the order of 5 to 15 per cent. of the total work done on the test-piece.

The object Mr. Russell had in view was to consider dispassionately whether a vitreous phase was present in a cold-drawn metal, but instead of doing so he immediately assumed the existence of two phases and then tried to correlate one with the so-called "vitreous phase."

In the first place it was not at all obvious that an increase in the internal potential energy of a metallic crystalline conglomerate was necessarily accompanied by a change of phase; secondly, it was very difficult to see that the so-called "plastic flow" of such a conglomerate necessarily involved the simultaneous existence of the liquid phase. In his (Mr. Brown's) opinion Mr. Russell would find it impossible to justify either of those assumptions.

An increase of potential energy might be effected by increasing the distance between the atoms of the metal, either in the space lattices of the crystals, should that be possible, or by increasing the average distance between the surfaces of the crystals themselves. So far it had not been possible to determine any difference between the lattice

¹ *Journal of the Iron and Steel Institute*, 1920, No. I. p. 341.

² *Mitteilungen über Forschungsarbeiten*, Heft 41, 1907.

spacing of metals in the strained and unstrained conditions, and the experiments of Kahlbaum and Sturm,¹ and later those of Goerens,² on cold-drawn steel wire indicate a maximum difference of density between the cold-worked and annealed material of the order of 0.25 per cent. only. If 5000 foot-pounds could be expended in increasing the volume of a cubic inch of iron the density would be diminished by about 4.9 per cent.—a figure nearly twice that given by Landon³ as the result of his experiments on the torsion of bars.

It was conceivable that an atom, or several atoms, might be detached by force from the space lattice of the crystal of which they formed a part, but it did not necessarily follow that they would then be in a condition corresponding to the liquid state, and each have the same amount of energy, or even as a group have the amount of energy as in that state.

During the process the potential energy of the whole system, comprising the original crystal and the detached atoms would be increased, but the energy of translation of the detached atoms might be very small indeed as compared with their potential energy.

If those detached atoms were moved to another part of the surface of the crystal and released they would return towards the crystal, and some of the potential energy of the system would be converted into kinetic energy, which would appear as heat when the atoms again came to rest; not necessarily each at a definite point of the space lattice, but as near to such positions as might be possible.

The detached atoms might be, and probably would be, sufficiently numerous in themselves to form a small submicroscopic crystal, and it was evident that if the process were repeated a sufficient number of times the final result of detaching and translating those small atomic groups would be a so-called vitreous layer.

During that process none of the material would have been liquefied, but a certain amount of the work done would have been converted into heat, and the remainder, a small quantity only, as indicated by the results of Hort's experiments, would be in the form of potential energy which could only be recovered by annealing the material, or otherwise allowing the detached atoms or atomic groups to return to their original close relationship, or, in other words, to positions in the lattice of the crystal from which they were originally taken, or some other crystals.

That process would have results entirely in accordance with the author's experience as described at the foot of p. 502, where he stated that the energy could not be all kinetic or all potential, for undoubtedly the test-piece got warm.

On p. 509 the author calculated the amount of energy required to

¹ *Zeitschrift für anorganische Chemie*, 1905, vol. xlv. p. 217.

² *Ferrum*, 1913, vol. x. p. 232, Fig. 215.

³ Landon, "Change of Density of Iron due to Overstrain," *Journal of the Iron and Steel Institute*, 1923, No. I. p. 455.

detach an atom of iron from its lattice, but he had apparently overlooked the fact—as far as his argument in support of the vitreous phase was concerned—that if all the energy, 1.073×10^{-14} ergs, were stored in it and it was consequently in a condition corresponding to the liquid state, it would have a velocity of translation of 150 metres per second. That was somewhat greater than the average speed of a polishing pad.

It will be recognised that the statement attributed to Dr. Rosenhain that the “amorphous” phase was—from the point of view of the phase doctrine—identical with the “liquid phase”—was not correct if the “amorphous” phase was formed in the manner indicated above.

With reference to the electromotive force of cold-worked iron against the unworked or annealed material, it seemed desirable to point out that the results of Spring, quoted on p. 507, all relate to metals of different structure, and with much larger lattices, than that of α -iron; and unfortunately there did not seem to be any figures available for them similar to those set out in Tables II. and III. on p. 511.

Tammann¹ had advanced very strong arguments against the possibility of the existence of the vitreous or amorphous phase, and those arguments did not appear to have been successfully controverted.

Mr. RUSSELL, in reply, thanked Mr. Brown for his criticism of the paper. In the original paper it had been stated on p. 351 that the quantity of work denoted by D should represent the work which went to increase the internal energy of the metal, and no doubt would be claimed by the supporters of the amorphous phase theory as the latent heat of formation of that substance. In the present paper, he (Mr. Russell) had modified that view, and suggested that the work D was expended in the formation of the liquid phase, and only that portion which corresponded with the latent heat of liquefaction was retained to increase the potential energy of the cold steel. For instance, out of 5000 foot-lbs. of work per cubic inch, only $\frac{49.35}{275.95} \times 5000 =$

895.4 foot-lbs. went to increase the potential energy. That was about 9 per cent. of the total work of rupture for steel A, to 13 per cent. for steel F. He thought that those figures were in remarkably good agreement with Hort's figures, and made it unnecessary to deal further with several of the points raised by Mr. Brown.

The amorphous theory had been more or less generally accepted, in spite of the fact that the expounders of that theory had not supported it with any quantitative data. For any theory to be sound, it was essential that it should not violate any well-established principles. One such principle was that an increase in the potential energy

¹ *Aggregatzustände*, Leipzig, 1922, p. 188 *et seq.*

of a metallic conglomerate (or any other system) was accompanied by a change of phase. That that may be a change from one solid phase to another solid phase, or from a solid phase to a liquid phase, did not alter, in the slightest degree, the basic principle.

Another indisputable fact was that if iron were to be converted from the solid to the liquid, whilst the two phases were contact, a minimum temperature of 1500° C. had to be reached. It was that aspect which he (Mr. Russell) had examined quantitatively, and his results showed that the "truly vitreous" theory was quite sound.

Iron and Steel Institute.

NOTE ON A VALUE FOR THE SURFACE
TENSION OF IRON SULPHIDE.

By E. J. L. HOLMAN, B.Sc. (UNIVERSITY OF BIRMINGHAM).

THOUGH much attention has been devoted to the influence of sulphur in iron and steel, the mechanism of its diffusion and the exact causes of its injurious effects under certain conditions are still imperfectly understood. It is evident that surface tension must play an important part in the diffusion or segregation of sulphur in iron and steel, but hitherto no determination of the value of the surface tension of iron sulphide has been available, and conjecture has sometimes taken the place of accurate information.

Levy¹ has stated that the sulphide, "being possessed of a marked viscosity and surface tension, prevents the coalescence of the cementite, which appears to be a preliminary to its breaking down to ferrite and free carbon." He² also refers elsewhere to "these minute sulphide films having a high surface tension," and says that "sulphur acts physically by a lowering of melting points and surface tension."

Thompson³ says that "Sulphide inclusions in steel exhibit well the effect of surface tension in rounding their outlines, so that in the cast state they are in general perfect spheres."

More recently Cosmo Johns⁴ has pointed out, with reference to the surface tension of steel, that while it is not difficult to demonstrate the existence of surface energy qualitatively, a quantitative value for the surface tension of liquid steel is not easy to obtain. Although giving no figures, he states that values have been determined by measuring from crest to crest the ripples on a solidified

¹ D. M. Levy, "Iron, Carbon, and Sulphur," *Journal of the Iron and Steel Institute*, 1908, No. II. p. 65.

² D. M. Levy, "Constitution of Cast Irons and Carbon Steels," *ibid.*, 1910, No. I. pp. 418-419.

³ F. C. Thompson, "The Influence of Surface Tension upon the Properties of Metals, especially of Iron and Steel," *ibid.*, 1917, No. I. p. 167.

⁴ Cosmo Johns, "The Solid and Liquid States of Steel," *Journal of the West of Scotland Iron and Steel Institute*, 1918-1919, vol. xxvi. p. 38.

mass of steel, a method of determining surface tension first used successfully with aqueous solutions by Lord Rayleigh.¹

The important question of surface tension as it affects the properties of metals in general has been the subject of much inquiry within recent years. Smith² has dealt at length with the surface tension of molten metals, and in addition to collecting and arranging the work done on the subject previous to his research, has given values for the surface tension of ten common metals, and has applied his results to an explanation of the cohesive forces at work in metals and alloys. His method was to measure the capillary depressions of molten metals in tubes of fine bore, which was an extension, with added refinements, of the well-known method of determining the surface tension of a liquid by its ascent in a capillary tube. He worked from the equation :

$$T = \frac{h \cdot r \cdot \rho \cdot g}{2}$$

Undoubted disagreements occur in the values obtained for the surface tensions when different methods of determination are adopted, and although from the accuracy of Smith's work his results are probably the most trustworthy, the question of exact determination is still open, as will be seen from Table II., which gives a comparison of values obtained by other workers.

For the purpose of obtaining an approximate value for the surface tension of iron sulphide, it was decided to adopt a method to which Professor T. Turner³ drew attention in the 1921 May lecture to the Institute of Metals. The procedure is a modification of the well-known drop-method, and consists in pouring the metal to be examined on to a flat surface and measuring the thickness of the plate. The surface tension of a metal at a high temperature near to its freezing point can then be calculated by means of the equation,

$$T = g d \frac{h^2}{4},$$

where T is the surface tension in dynes per centimetre, g is 981, d the density of the metal, and h the thickness of the plate.

¹ *Philosophical Magazine*, vol. xxx. p. 386.

² S. W. Smith, "The Surface Tension of Molten Metals," *Journal of the Institute of Metals*, No. 2, 1914, vol. xii. p. 168 ; also No. 1, 1917, vol. xxii. p. 65.

³ T. Turner, "The Casting of Metals," *Journal of the Institute of Metals*, No. 2, 1921, vol. xxvi. pp. 9-11.

The following brief theoretical concept will explain the method used :



FIG. 1.

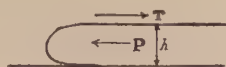


FIG. 2.



FIG. 3.

FIGS. 1, 2, and 3.—Showing possible Sections of Cast-Metal Plate.

Figs. 1, 2, and 3 represent possible sections of a plate of cast metal. When the metal is fluid and just before it freezes there are two main forces at work : T , the force of surface tension acting in one direction, and a force P , due to hydrostatic pressure acting in the opposite direction.

Smith (*loc. cit.*) has stated that " Theory and observation have from the earliest recorded work agreed upon the necessity of assuming a finite angle of contact between liquids and solids which do not wet "—an angle which will vary according to the nature of the solid with which the molten metal is in contact.

If the plate make an angle θ with the surface on which it is cast, as shown in Fig. 1, the relationship from which T can be deduced may be written :

$$T(1 + \cos \theta) = \frac{1}{2} g d h_1^2, \text{ or } T = \frac{g d h_1^2}{2(1 + \cos \theta)}.$$

If the state of affairs on solidification be as represented in Fig. 2, T can be deduced from the equation,

$$T = \frac{g d h^2}{4},$$

by assuming that the last element of the liquid surface to freeze is practically parallel to the horizontal surface, θ in the limit becoming zero, $\cos \theta$ approaching 1.

A method of calculation which applies to either of the cases represented in Figs. 1 and 2 is given by the equation,

$$T = \frac{g d h_2^2}{2}$$

where, as shown in Fig. 3, h_2 represents the distance, below the surface of the plate, of that element of its profile which is vertical.

It may be pointed out that even when θ , as in Fig. 1,

differs considerably from zero, and even if it be as large as 30° , the error introduced by assuming it to be zero and applying the equation,

$$T = \frac{gdh_1^2}{2(1 + \cos \theta)}$$

would not exceed 10 per cent.

Before applying the method to iron sulphide it was considered advisable to carry out experiments with the five common metals, lead, zinc, copper, tin, and aluminium, the surface tensions of which had been observed by other workers. It was at once found that widely varying results were obtained if globules were employed, and after a number of trials the following method was adopted. Relatively large masses of the metals, namely, 800 grammes, were melted in a crucible and poured at a temperature 20 per cent. above their respective melting points on to a smooth iron surface which had been warmed to 80° C.

The resulting plates, roughly circular in form, showed, for each metal, a distinct difference in thickness. With each individual plate, however, there were variations in the value of h , a maximum in every instance being reached at a point near the edge of the casting where solidification of the poured metal had first taken place. This maximum value was in each case recorded, as it was at this point that the forces of surface tension had had most play while the cast plate was in the fluid state.

The following table gives the results obtained :

TABLE I.

Metal.	Melting Point.	20 per Cent. above Melting Point.	h Centimetres. Average of Three Experiments.	Density. Grammes/c.c.	$T = \frac{gdh^2}{4}$ Dynes/cm.
	Degrees C.	Degrees C.			
Tin . . .	232	278	0.200	7.3	462
Lead . . .	327	392	0.145	11.3	375
Zinc . . .	419	503	0.241	7.2	635
Copper . .	1083	1299	0.260	8.8	940
Aluminium .	658	789	0.335	2.7	477
Iron sulphide .	980	1176	0.257	5.02	494.4

The above results, although following the same order, are all somewhat lower than the accepted values for the surface tensions

of the respective metals. It must, however, be borne in mind that the maximum value of h was at all times recorded, and in some instances this was difficult to obtain with a high degree of accuracy, owing to the uneven character of the surface.

If Smith's results are to be taken as a standard (and it will be seen from Table II. that his values differ somewhat from those obtained by Quincke, Siedentopf, and Grunmach, employing other methods), the results given at least point to the suitability of the present method for giving an approximate determination of the surface tension of a metal.

TABLE II.—*Comparison of the Values for the Surface Tension of Metals.*

Dynes per Centimetre.

Metal.	Quincke.	Siedentopf.	Grunmach.	Various.	Hogness. ¹	Smith. ²	Author.
Selenium .	92.5	...	...	...	...	...	...
Antimony .	317.2	...	...	...	...	274	...
Bismuth .	464.9	429.5	...	...	376	346	...
Lead .	{ 535.9 457 $\frac{\text{mg.}}{\text{mm.}}$	{ 509.5 519 $\frac{\text{mg.}}{\text{mm.}}$	{ 482 $\frac{\text{mg.}}{\text{mm.}}$ 491.2	...	444	424.5	375
Mercury .	547.2	...	{ 491.2 405.0	Stöckle 435.6	...	447.5	...
Tin .	{ 681.2 598 $\frac{\text{mg.}}{\text{mm.}}$	{ 612.4 624 $\frac{\text{mg.}}{\text{mm.}}$	{ 352 359	...	531	480	462
Aluminium	No values recorded			...	...	520	477
Zinc .	{ 967.4 1103.7 }	...	...	...	758	707.5	635
Cadmium .	815	832	...	...	630	...	...
Silver .	782.4	...	...	Graden- witz 751.0	...	858	...
Gold .	581	...	...	Heyd- weiller 612.2	...	1018	...
Copper .	...	...	...	...	...	1178	940
Iron sulphide	...	...	...	...	...	...	494.4

It is not claimed that the number 494.4 obtained for iron sulphide represents an exact determination, but there is every reason to believe that the figure of about 500 indicates the order

¹ T. R. Hogness, "The Surface Tensions and Densities of Liquid Mercury, Cadmium, Zinc, Lead, Tin, and Bismuth," *Journal of the American Chemical Society*, 1921, vol. xliii, p. 1621.

² *Loc. cit.*

of the surface tension of iron sulphide and the relative position of this compound when compared with the common metals.

There is thus no evidence to support the view that iron sulphide has a high surface tension, and it appears to be clear that the surface tension of iron sulphide is not more than half that of iron itself. This is what might be expected from what is known to occur in other cases. A value for the surface tension of iron has been calculated from its internal pressure : this value is 1244 dynes per centimetre. Sulphur, on the other hand, according to Zickendraht, has a surface tension of only 57 dynes per centimetre, a value lower than that of water, so that a relatively low value for the surface tension of iron sulphide seems reasonably certain.

This fact must have an important bearing on the question of the diffusion of iron sulphide in iron, and its effect on iron carbide. To these matters attention is being directed, and it is hoped that the results will in due course be brought before the Institute.

In conclusion, the author wishes to tender his best thanks to Professor T. Turner, M.Sc., A.R.S.M., of the University of Birmingham, for much valuable help and suggestion during the course of the work, and also to Dr. S. W. Smith, of the Royal Mint, for his friendly criticism.

CORRESPONDENCE.

Dr. F. C. THOMPSON (Manchester) wrote that although the paper by Mr. Holman dealt with a very interesting and important subject, it was impossible not to see certain aspects of the experimental work which could not but lead to much uncertainty in the values obtained for the surface-tension of iron sulphide. The method, although suitable for materials which were not affected by the air, was open to the serious objection in other cases that surface oxidation would occur and lead to values for the constant which might be very far from the true ones. In general one would expect that if oxidation had occurred the value would be lowered. A second important point was that the sulphide used was apparently far from pure. Here again the probabilities were that the surface tension would be reduced. The value given in the paper could, therefore, only be regarded as being a lower limit, the extent to which it fell below the true value being uncertain.

It would be noted that all Mr. Holman's results for metals were distinctly lower than those of other workers. One could not, therefore, accept the statement that "there is every reason to believe that the figure of about 500 indicates the order of the surface tension of iron sulphide." It was difficult without further work to place much credence in the statement: "There is no evidence to support the view that iron sulphide has a high surface tension, and it appears to be clear that the surface tension of iron sulphide is not more than half that of iron itself." It cannot be too clearly stated that the method used by the author was not suitable for the purpose to which it was applied.

Iron and Steel Institute.

SOME EXPERIMENTS ON GRAIN GROWTH IN IRON AND STEEL. (PART I.)

By L. E. BENSON, M.Sc., AND F. C. THOMPSON, D.MET., B.Sc. (MANCHESTER).

DESPITE the acknowledged importance of the grain size of a crystalline aggregate in its effects on the mechanical properties, there is very little published work of a quantitative nature dealing with crystal growth during annealing in the ferrous materials. It appeared, therefore, to be worth while examining the subject. The present work deals only with a portion of the whole problem, since it is confined to temperatures not exceeding 800° C., and deals with the influence of the composition only so far as carbon and manganese are concerned. It is intended to extend the scope of the research in the near future.

METHOD OF INVESTIGATION AND MATERIALS USED.

Materials Used.—The accompanying table (Table I.) gives analyses of the materials used in this research, with the appropriate identification marks.

TABLE I.

Material.	Mark.	C per Cent.	Mn per Cent.	Si per Cent.	S per Cent.	P per Cent.
Armco iron . . .	A	Guaranteed purity, 99.84				
Pure carbon . . .	B	0.16	0.05	0.08	0.030	0.018
Crucible steels . . .	C	0.37	0.05	0.08	0.028	0.020
	D	0.58	0.14	0.09	0.037	0.017
Open-hearth steel . .	E	0.41	0.54	0.13	0.07	0.04
Acid Bessemer steel .	H	0.40	0.89	0.08	0.06	0.06

The Armco iron was given specially for the research by the Shelton Coal and Iron Co., Ltd., to whom the authors wish to express their gratitude.

The steels were chosen so as to include a series in which the carbon and the manganese varied separately, in order that the

effect of these elements on the grain size and the rate of grain growth could be observed.

To determine the effect of time and temperature on the grain size, specimens of all the materials were normalised at 950° C. and then annealed for different periods at four different temperatures, viz. 350° C., 500° C., 650° C., and 800° C. At each temperature specimens were annealed for 1 hour, 5 hours, 20 hours, and except in the case of the 800° C. treatment, 72 hours. At 500° C. a 10-hour anneal also was included.

Annealing.—The annealing of the specimens at 350° C., 500° C., and 650° C. was carried out in a vertical nichrome-wound resistance furnace, inside which was placed a nichrome crucible containing the molten salt.

With careful manipulation the temperature of the salt bath could be kept within 5° C.

The composition of the salt baths employed for the different annealing temperatures were as follows :

- | | | | | |
|---------------------------|-----------------|--------|--------------------|-------|
| 1. Annealing at 350° C. | sodium nitrate | 90 % | potassium chloride | 10 %. |
| 2. " " 500° C. | " " | 85 % | " " | 15 %. |
| 3. " " 650° C. | barium chloride | 50 % | sodium | 33 %. |
| | | | potassium | 17 %. |
| 4. Normalising at 950° C. | " " | 100 %. | | |

Except in the case of the 0.6 per cent. carbon steel, no trouble was experienced through decarburisation, even after the somewhat lengthy annealings that were made. It was noticed, however, that the nitrate baths—particularly at 500° C.—attacked the specimens with the formation of a brown deposit, presumably oxide. There did not appear to be any intercrystalline penetration, nor was the attack necessarily accompanied by decarburisation. On the other hand, all those specimens annealed at 500° C. in a bath containing sodium nitrate were found on micro-examination to have developed a structure near the surface suggestive of the formation of nitride of iron. This question of nitrogenisation has been discussed more fully by one of the authors.⁽¹⁾

Annealing at 800° C. for prolonged periods was found to be impracticable, owing to the excessive volatilisation and creeping of the molten salt. These annealings, therefore, were made in a horizontal tube furnace, in which the specimens were placed, packed round with iron filings. At the end of an experiment the

specimens were invariably found to be "bright annealed." To prevent diffusion of the carbide from one specimen to another, or to the iron filings, the specimens to be annealed were wired in a group and then coated with plaster of Paris.

Estimation of Grain Size.—The method of arriving at a figure for the average grain area worked out for the purpose of this research is very similar to that advocated by Jeffries.

An image of the etched specimen was projected on to the ground-glass screen of a Zeiss photomicrographic apparatus, and an area typical of the whole sample selected. The number of grains falling within a square drawn on the ground-glass screen was counted, each grain being ticked with a pencil mark. The grains falling across the boundary were counted as being each equivalent to half a grain. The actual area occupied by the grains counted was obtained by substituting an engine divided scale divided into 0.01 millimetre in place of the specimen and measuring the length of side of the square. From the figures obtained, the average grain area of a homogeneous alloy is easily calculated.

The average number of ferrite grains counted per specimen during this work was between five hundred and six hundred.

The counting of the ferrite grains presented no great difficulty, nor did the counting of the pearlite in the low carbon steels, since each grain was completely surrounded by ferrite. In the higher carbon steels, however, no continuous network of ferrite existed, the pearlite grains frequently lying side by side. With very careful etching, and the use of a moderately high magnification, it was found possible to distinguish grain boundaries in the pearlite by the abrupt change in structure of the eutectoid. At the same time it must be freely admitted that a considerable amount of judgment had at times to be used. To reduce the possibility of error due to the personal element to a minimum, the pearlite grains in each series, *e.g.* in the plain 0.6 per cent. carbon steel after annealing for varying periods at 350° C., were counted on the same day.

STATEMENT OF RESULTS.

The results of the experiments carried out are embodied in the following tables (Tables II. and III.).

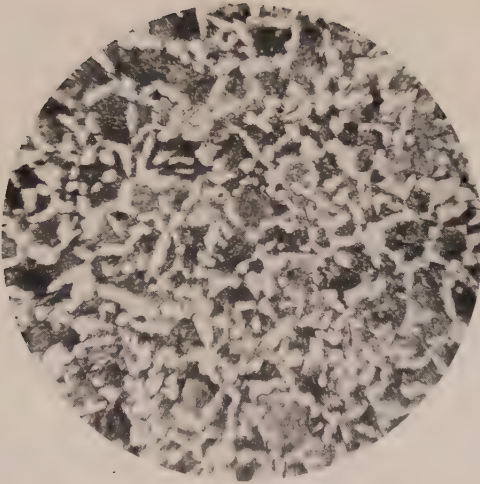
TABLE II.—*Armco Iron.*

Period of Annealing.	Number of Ferrite Grains per Square Millimetre.			
	350° C.	500° C.	650° C.	800° C.
Normalised	335	373	373	335
1 hour	272	315	279	272
5 hours	272	282	247	206
10 " . . . . .	...	257	...	...
20 "	259	232	244	176
40 " . . . . .	...	...	...	157
72 "	259	212	244	...

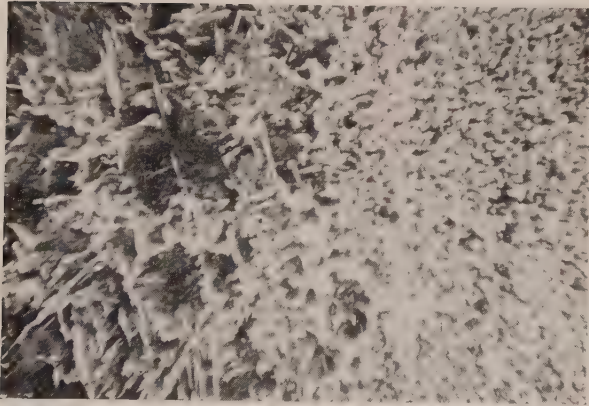
TABLE III.—*Steels.*

Steel.	Period of Annealing.	Number of Grains per Square Millimetre.							
		350° C.		500° C.		650° C.		800° C.	
		Ferrite.	Pearlite.	Ferrite.	Pearlite.	Ferrite.	Pearlite.	Ferrite.	Pearlite.
B.	Normalised	1243	452	1204	391	1204	391	1243	452
	1 hour	1136	413	1008	285	304	177	989	305
	5 hours	1040	422	298	139	275	153	930	282
	10 "	...	...	229	136	...	...	...	...
	20 "	1032	430	218	120	...	...	755	264
	72 "	988	420	224	115	258	137	638	197
C.	Normalised	482	320	502	336	502	336	482	320
	1 hour	463	315	467	309	378	295	802	479
	5 hours	420	278	428	300	362	291	830	469
	10 "	...	...	393	277	...	...	...	...
	20 "	392	284	344	267	292	229	794	485
	72 "	356	271	309	246	349	219	681	428
D.	Normalised	518	214	507	229	507	229	518	214
	1 hour	460	214	552 ¹	271 ¹	468	177	1200	770
	5 hours	432	206	626 ¹	252 ¹	515 ¹	213 ¹	1145	725
	10 "	...	...	454	206	...	...	...	...
	20 "	427	203	682 ¹	334 ¹	715 ¹	301 ¹	1105	677
	72 "	408	201	530 ¹	229 ¹	323	138	990	596
E.	Normalised	934	390	955	395	955	395	934	390
	1 hour	840	372	811	398	793	408	1330	624
	5 hours	794	380	799	416	700	367	1041	521
	10 "	...	...	673	385	...	...	...	...
	20 "	767	349	666	372	656	356	985	458
	72 "	794	372	...	...	653	336	858	434
H.	Normalised	2540	1050	2070	1081	2070	1081	2540	1050
	1 hour	2310	950	1751	895	1715	887	3518	2135
	5 hours	2240	926	1651	827	1670	826	2110	1175
	10 "	...	...	1575	802	...	...	...	...
	20 "	2220	918	1575	750	1568	734	1678	950
	72 "	2195	1005	1430	626	452	680	1430	834

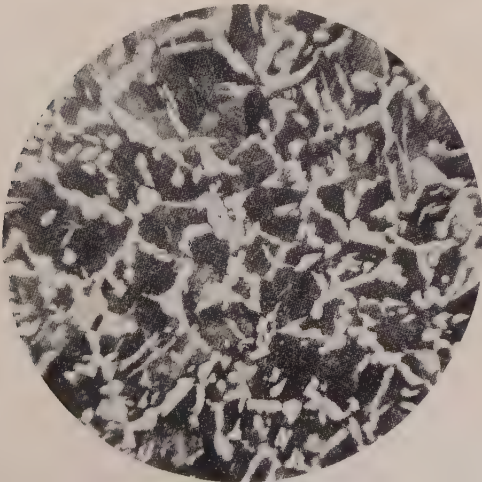
¹ Specimen decarburised.



Steel D. 20 hours at 650°C. (decarbonised)
× 180.



Steel D. 20 hours at 800°C. × 45.



Steel D. Normalised.
× 180.

Since it is not possible in the case of the steels—particularly those containing manganese—to calculate the average grain area without making certain assumptions regarding the relative areas occupied by pearlite and ferrite, no attempt has been made to do this in the case of Armco iron.

The number of grains of ferrite and pearlite given in the tables have been calculated per square millimetre of actual specimen surface.

DISCUSSION OF RESULTS.

Grain Growth in Pure Iron.

Microscopical analysis of the Armco iron showed slight traces of segregated carbide in the centre of some specimens, but this invariably proved to be so localised that no difficulty was experienced in making all determinations on carbide-free areas. The results obtained can, therefore, be taken as representative of the behaviour of practically pure ferrite.

It was anticipated that annealing up to 800° C. would cause grain growth in every case. That this has been so is immediately obvious from graphs I to IV (Fig. 1). "Grain size" is here plotted against time.

All four curves are of the same character, and reference to the curves for ferrite in steel shows that these too are similar where the annealing temperature has not exceeded that of the carbide change point.

Influence of Annealing Temperature and Period of Annealing.

Almost the only quantitative work on grain growth in a steel containing 0.07 per cent. carbon has been published by Joisten.⁽²⁾ His curves for annealing at 600° C. and 700° C. are of a different type to any of those obtained in this work.

The Armco iron annealed at 350° C. (curve I) shows very distinct signs of grain growth after only one hour, but the rate of growth falls off on prolonged heating until, after twenty hours, an approximately stable condition is reached.

On annealing at 800° C. a very rapid diminution in the number of ferrite grains per unit of area takes place, but, as before, the

rate of growth tends to fall off on prolonged annealing ; though after forty hours growth still continues.

The 500°C . annealing curve is of the same type, and intermediate between the 350°C . and the 800°C . curves, as would be expected ; but the 650°C . curve is abnormal. Up to five hours the rate of grain growth appears to be intermediate between that at 500°C . and that at 800°C ., but from this point onwards practically no further growth takes place. The graphs for ferrite in the various steels all show the same phenomenon, with the exception of steels D and E. In the latter case, although the 500°C . and 650°C . curves do not actually intersect, they lie very close together ; whilst in steel D reliable figures at the lower temperature have not been obtained on account of decarburisation and diffusion.

From the above considerations, therefore, it appears that in the region of 650°C . the normal grain growth of pure ferrite, and of ferrite in some steels, is retarded. The investigations here dealt with throw no direct light on the nature of the retarding influence, but without assuming that some change takes place in the iron itself it seems impossible to account for the retardation.

Mode of Grain Growth in Ferrite.

It was noticeable that the grain boundaries became more regular and straighter with the elimination of re-entrant angles as the annealing was increased. Examination of the polished specimens after squeezing in a vice showed that this more regular grain shape is accompanied by a higher degree of perfection in the structure of the crystals, the slip-bands produced being straight after annealing, but generally curved and branched when normalised.

Effect of Time of Annealing on Grain Size of Steel.

The study of grain growth in steels on annealing falls under three heads according as the annealing has been (a) below the carbide change temperature, (b) above the upper critical point for the steel in question, or (c) at a temperature intermediate to the A1 and A3 points,

(a) *Steels Annealed below 700° C.*—The effect of annealing on pure ferrite has already been discussed. The changes taking place in ferrite in steels on annealing appear to be of precisely the same nature as in Armco iron, as long as the annealing temperature does not exceed that of the lower critical point for the steel.

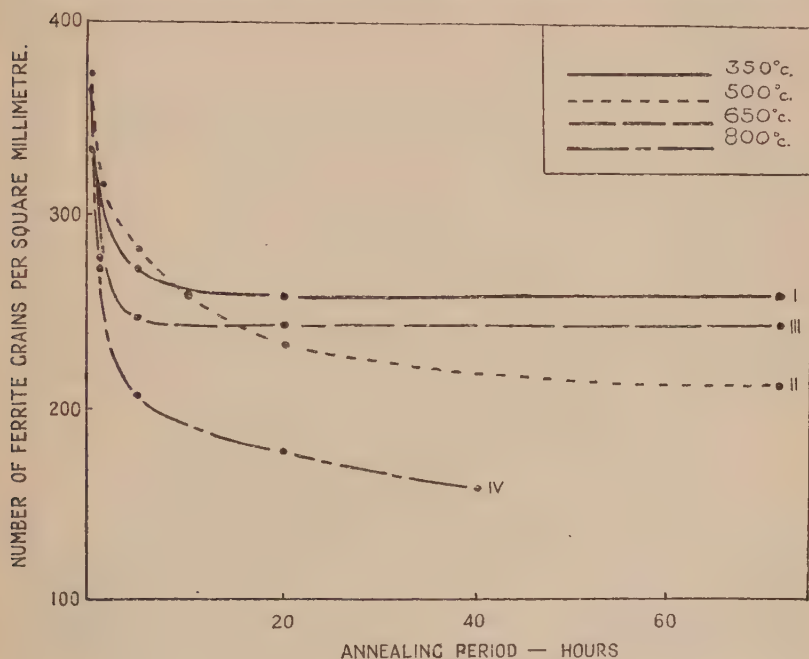


FIG. 1.—Grain Growth in Armco Iron.

That this is so is made evident from a study of the grain-growth curves for ferrite in the two cases (see Fig. 1, and Figs. 2 to 6).

It was not anticipated that annealing below 700° C. would have any appreciable effect on the distribution of the carbide, but the curves for pearlite (Figs. 7 to 11), when worked out, proved to be of precisely the same type as for ferrite. Had decarburisation taken place this might have accounted for the diminishing number of pearlite grains on annealing. Except in the high carbon steel, however, decarburisation effects were not observed even after prolonged heating. Further, the maximum apparent growth takes place within the first few hours, and in the few cases where

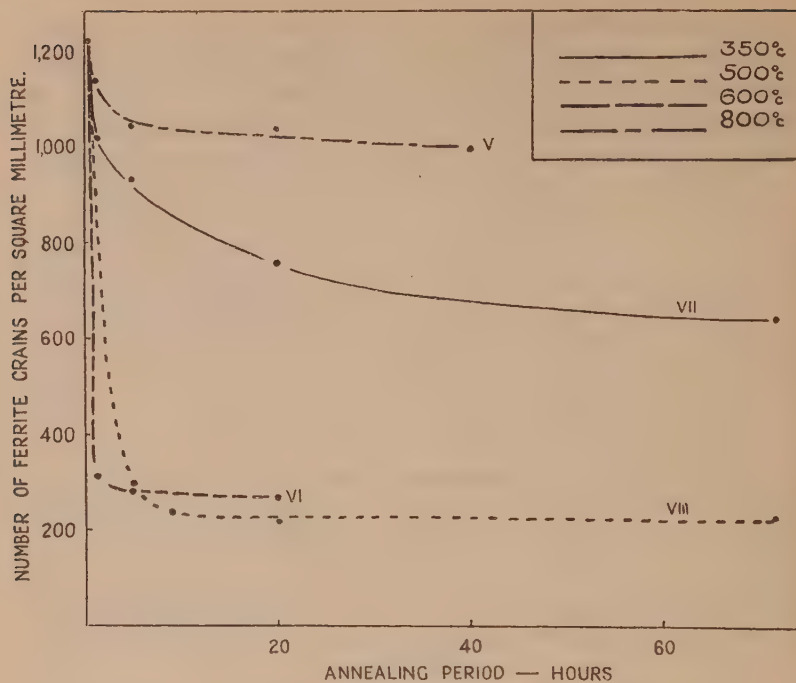


FIG. 2.—Grain Growth of Ferrite, Steel B.

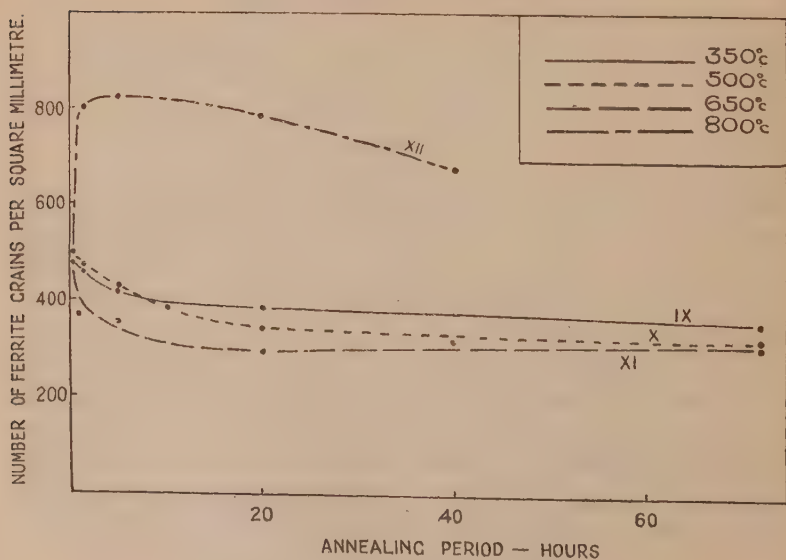


FIG. 3.—Grain Growth of Ferrite, Steel C.

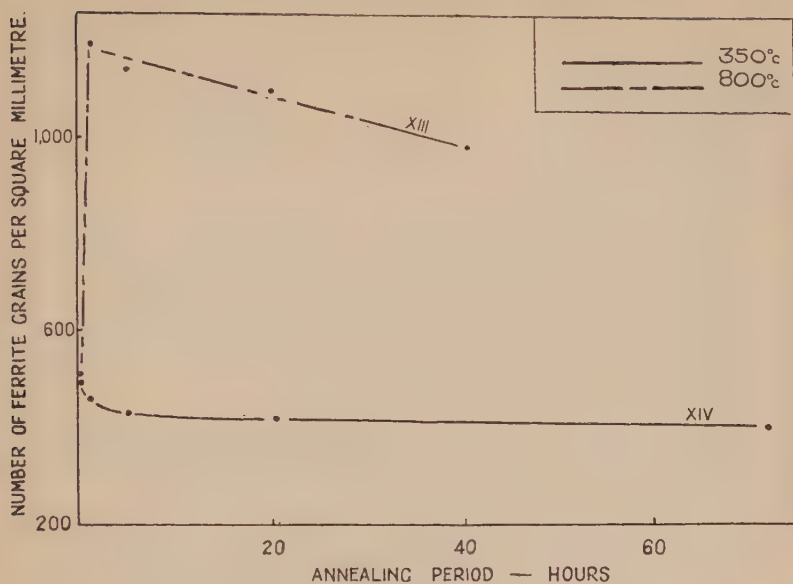


FIG. 4.—Grain Growth of Ferrite, Steel D.

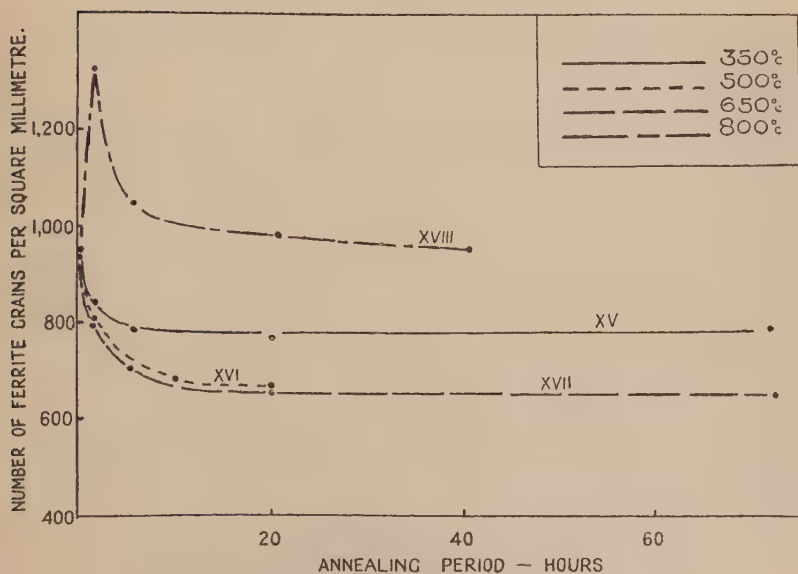


FIG. 5.—Grain Growth of Ferrite, Steel E.

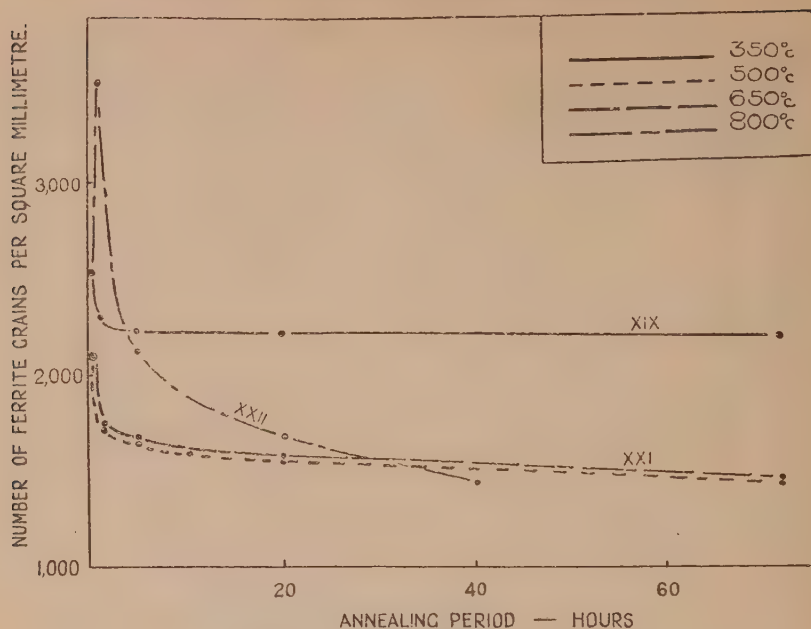


FIG. 6.—Grain Growth of Ferrite, Steel H.

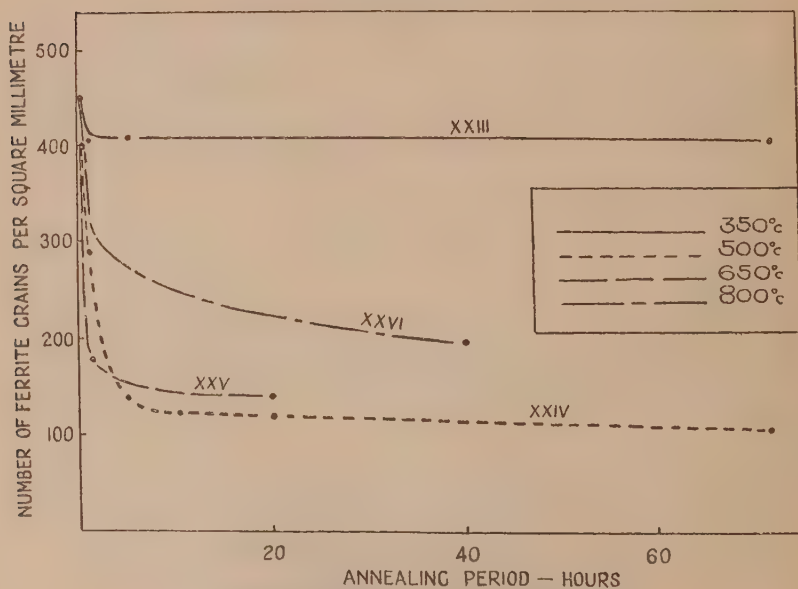


FIG. 7.—Grain Growth of Pearlite, Steel B.

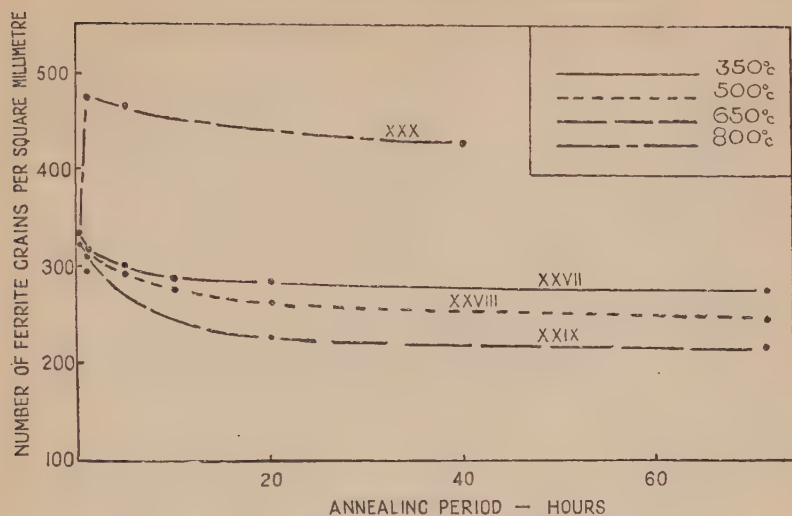


FIG. 8.—Grain Growth of Pearlite, Steel C.

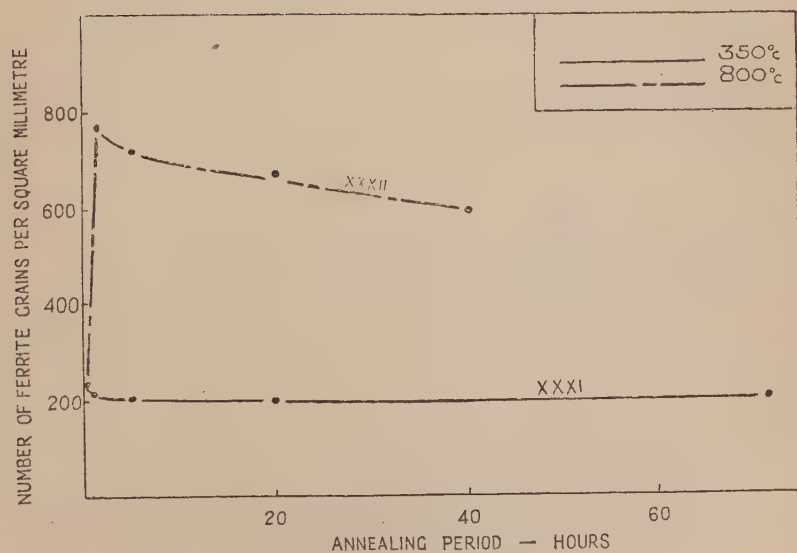


FIG. 9.—Grain Growth of Pearlite, Steel D.

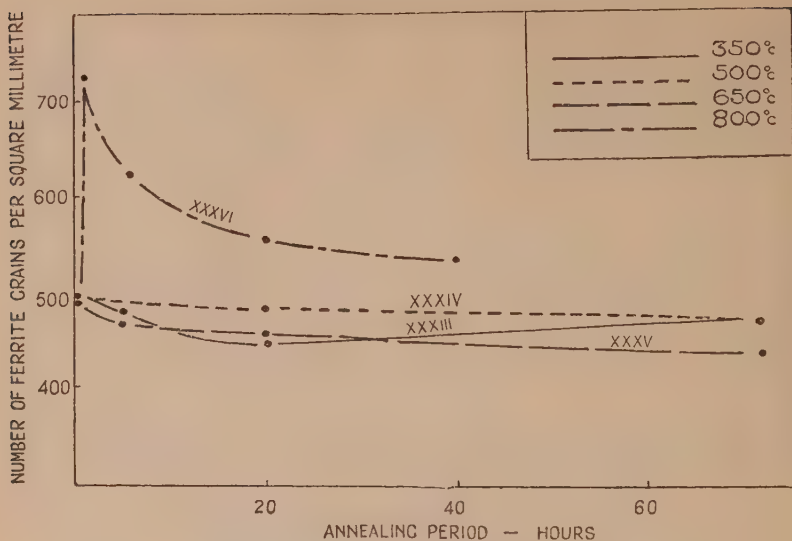


FIG. 10.—Grain Growth of Pearlite, Steel E.

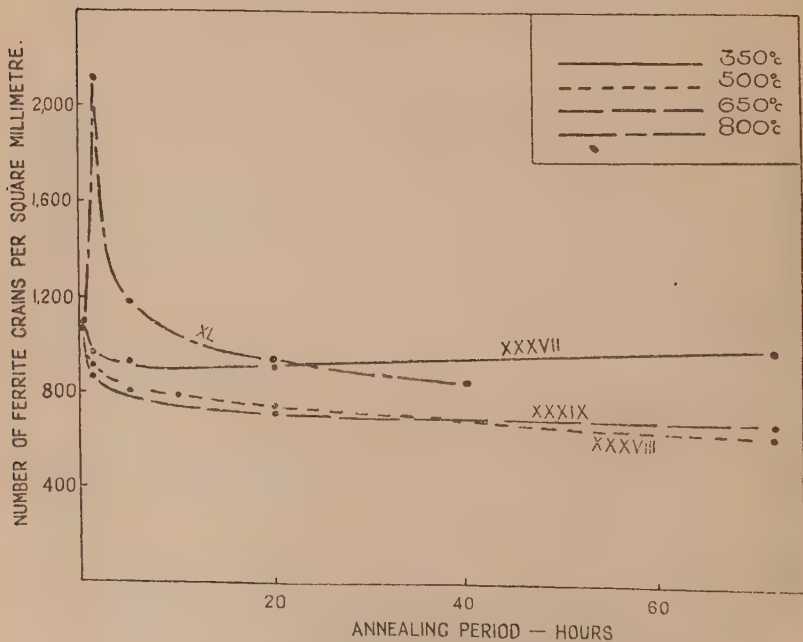


FIG. 11.—Grain Growth of Pearlite, Steel H.

decarburisation was detected a refining, and not a coarsening, of the grain was found to have taken place.

Microscopic examination revealed two reasons for this phenomenon. In the first place, it was observed that although the average pearlite grain after annealing was not perceptibly larger in size, the very smallest isolated grains visible in the normalised specimens were now absent.

The higher solubility possessed by small crystals as compared with that of large crystals of the same chemical composition is fully recognised, and the authors are inclined to believe that the solubility in α -iron of carbide in pearlite grains of small size and fine texture is sufficiently high to enable it to pass into solution in the ferrite at quite moderate temperatures. To avoid supersaturation a corresponding amount of cementite must be precipitated from solution on the already existing coarse-grained carbide lamellæ, without appreciably affecting the size of the pearlite grain as a whole.

The abnormalities in the grain size of ferrite which occur on annealing at temperatures in the region of 650°C. are reflected in the corresponding curves for pearlite, *e.g.* curves XXIV and XXV and XXXVIII and XXXIX.

The second reason for the pearlite grain growth is that in counting the pearlite grains an attempt was made to distinguish grains lying adjacent to one another. It was found that in the normalised structures this was quite possible with careful etching. The effect of annealing below the A_{c1} point, however, is to cause spheroidalisation of the cementite in the eutectoid. This tendency is sufficient to blur the laminated structure even before spheroidalisation can be definitely recognised, hence the definition of the grain boundaries between adjacent pearlite grains is lost.

(b) *Steels annealed above A_3 .*—The A_3 point of all the steels used containing more than 0.2 per cent. carbon falls below 800°C. ; hence on heating up to this temperature and on cooling down again phase changes take place, and the curves obtained under these conditions are not simple grain-growth curves. As would be expected, the effect of annealing for one hour at 800°C. has been to cause a distinct grain refining. That the ultimate distribution of ferrite and pearlite is to some degree dependent on the crystalline structure of the pre-existing austenite is well known

(for example, the angular overheated structure obtained when annealing within the austenitic range is carried out for too long a period or at too high a temperature), and although none of the steels annealed at 800° C. developed the overheated structure to a marked degree the effect of prolonged annealing is to be seen in the change of size of the ferrite and pearlite grains. Once the refining effect is complete, further annealing gives rise to a progressively coarser structure. This is well illustrated by the general shape of curves XIII, XVIII, XXX, XXXII, XXXVI, and XL.

(c) *Steels annealed at Temperatures between A and A3.*—The samples of steel B annealed at 800° C. are the only representatives of this class. Reference to graphs VIII and XXVI shows that there has been definite growth of both ferrite and pearlite grains. Another respect in which the specimens annealed at this temperature differ from those annealed below 700° C. is that even after the longest periods the eutectoid grains are laminated and not spheroidised.

Influence of Annealing Temperature.

The effect of annealing steels for a short period at various temperatures is shown in graphs XLV to LI. The grain-size values plotted are those obtained in steel for ferrite after heating for one hour at the different temperatures. At 950° C. the value plotted is that applying to the steel in the normalised conditions. As the normalising entailed a soaking of only twenty minutes at that temperature the value plotted is only approximately correct, but indicates the general shape of the curve well enough. The curve for the final asymptotic values for Armco iron has been inserted for comparison.

The graphs show that up to 650° C. the grain size increases as the annealing temperature is raised, and it is reasonable to expect that this will be true up to the temperature of the carbide change. This being so, a smooth curve will be obtained to 720° C. Beyond this temperature grain refining takes place, indicated in the graphs by a rapid rise.

The lower carbon steel, however, is not wholly in the austenitic state at this temperature, and the maximum refining has not taken place. The Ac3 point for the steel containing 0.4 per cent.

carbon and 0.89 per cent. manganese has been determined and found to be 805°C . The grain refining indicated by the 800°C . point on this curve is therefore the true maximum.

Annealing at temperatures exceeding that of the Ac_3 point results in a very decided coarsening of the structure, as is clearly shown by the steep fall of the curves, for steels containing 0.4 per

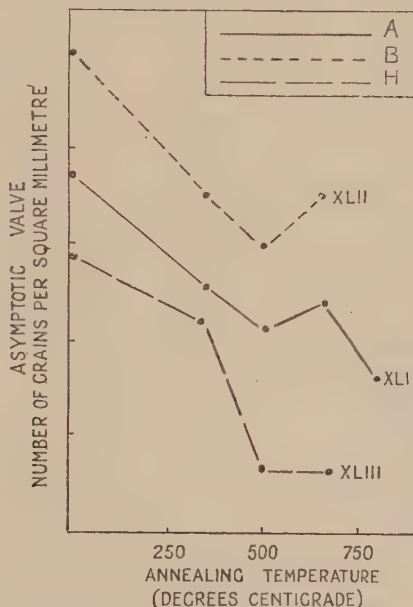


FIG. 12.—Influence of Annealing Temperature on Grain Size.

cent. or more carbon, between 800° and 950°C . In view of the fact that the annealing at the latter temperature was of comparatively short duration, the true curves will be even steeper than those plotted.

INFLUENCE OF COMPOSITION.

Considering first the effect of varying carbon contents on the normalised structure of iron-carbon alloys, grain-size figures obtained for Armco iron and steel B show that the addition of only 0.18 per cent. of this element causes a very pronounced

refining of the ferrite. (See graphs XLIV to XLVII.) This refining is probably attributable to a variety of causes. Pure iron, cooling from a high temperature, is free to grow immediately the temperature falls below 900°C ., whereas ferrite in a carbon steel does not start to form until a lower temperature is reached;

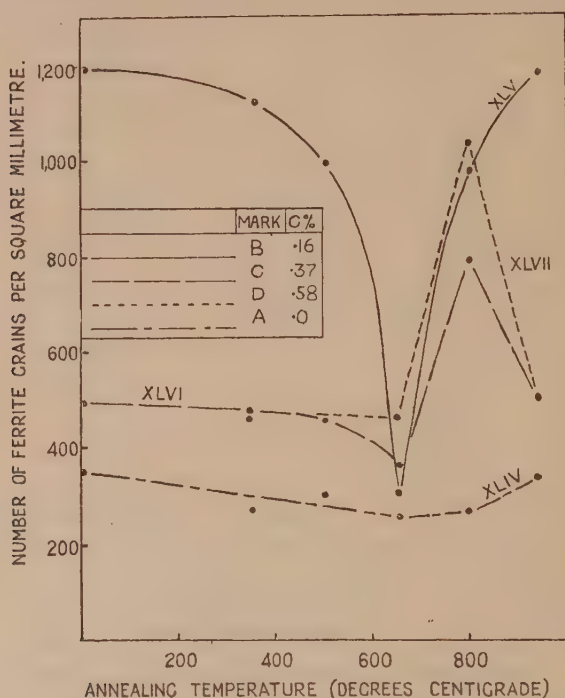


FIG. 13.—Influence of Carbon Content on Grain Size after Annealing for One Hour.

and even then the crystal growth is hindered by the obstruction of the residual austenite, and at lower temperatures by the pearlite transformation.

It has already been shown that the normal structure of a pearlite steel is dependent to a certain extent on the crystalline structure of the austenite from which it is formed; and the presence of carbide in solution in the austenite is more likely to retard than assist in the formation of the most perfect internal structure in the austenite. Particularly is this likely to have effect

when the diffusion that must take place between the Ar3 and the Ar1 points is considered.

A further possible explanation lies in the assumption that

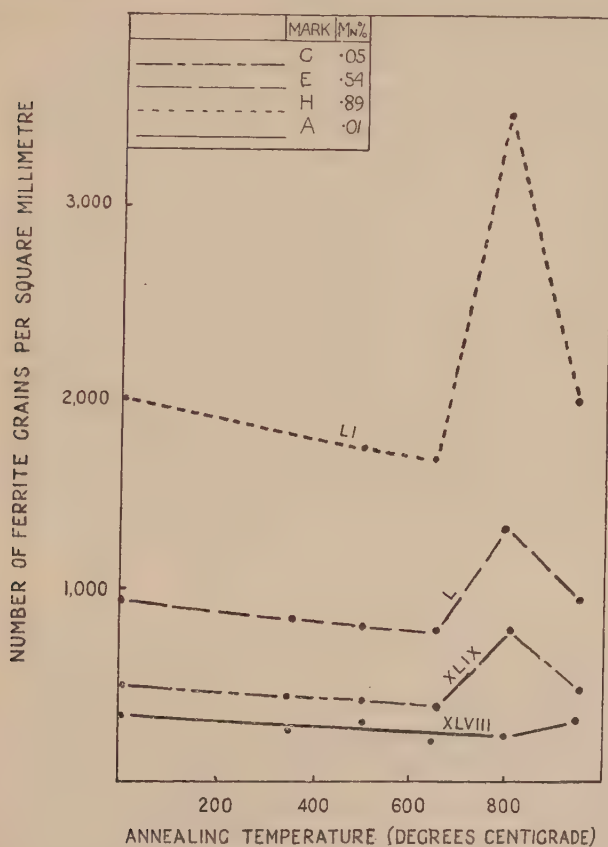


FIG. 14.—Influence of Manganese Content on Grain Size after Annealing for One Hour.

ferrite possesses a definite, if limited, solubility for Fe_3C below 690°C ., which decreases as the temperature falls. Under these conditions diffusion of Fe_3C through the ferrite on cooling down can safely be surmised, as a result of which the internal structure of the ferrite grains is disturbed and grain growth retarded. That diffusion of carbide through the mass does influence grain size

is amply demonstrated by steel D. The sample annealed for twenty hours at 650°C . possessed a much finer structure than did the normalised sample, the explanation being that in the former case the specimen was decarburised.

The presence of carbon in greater amount than 0.18 per cent. causes a steady decrease in the total number of crystal grains per square millimetre, owing chiefly to the fact that the total amount of free ferrite is decreasing. That the number of pearlite grains should also diminish with increasing carbon content is curious.

The effect of varying manganese content on the normalised structure of a 0.4 per cent. carbon steel is illustrated by graphs XLVIII to LI. The refining influence of manganese is clearly shown, and is common both to the ferrite grains and to the pearlite grains. As before, the structure of the steel containing the highest manganese content is invariably the finest. The influence of manganese in this respect is very powerful, and the curves above mentioned constitute strong evidence in favour of the use of steels containing a high percentage of this element when it is particularly desirable to guard against overheating.

EFFECTS OF DIFFUSION.

The results of the measurements on the 0.6 per cent. carbon steel, though not of much importance in connection with the main feature of the work, are of much value in another direction. This steel was found to be very irregular in structure (Fig. 17), an irregularity which persisted despite prolonged heating. That the structure did not revert to a normal one as a result of annealing is a matter of interest in that it indicates that such an irregular material, in which the irregularity is due to the initial cast condition, will, in spite of all that may be done later, still show the same objectionable feature. It will be noted from Table III. that, except at 350°C ., annealing was accompanied by a refining action which in the case of the 800°C . treatment reached a value twice that as normalised. Commencing with a ferrite grain number of just over 500 per square millimetre, after five hours' annealing at 800°C . it had become 1145. Even at 500°C . the effect is noticeable. Further, the pearlite shares in this refining, and after

seventy-two hours at 800° C. the pearlite grains are nearly three times as numerous as they were in the normalised state.

The explanation of these curious facts can only be found in the diffusion which is set up. The process of diffusion, as Andrew and Higgins⁽³⁾ have shown, produces a decrease of the grain size, with the result that in an irregular aggregate the attempt to bring about the uniformity of structure must be accompanied by considerable re-arrangement. It is as a result of this fact that a malleable iron does not show the angular structure which would be expected from such an overheated material, and that a cemented steel which has been heated for several weeks to excessively high temperatures also fails to show its effect. Decarburisation also leads to diffusion and, as has been seen, the grain size is much smaller even after prolonged heating than that of a steel uniform in structure. The following suggestion is made with some hesitation, but it appears to be true, that if a steel is to be heated to a high temperature for a long time it should be done in a somewhat oxidising atmosphere, so that there may be sufficient decarburisation to initiate diffusion to an extent that will balance the grain growth which would otherwise occur. In this way the coarse structure resulting from overheating would be appreciably reduced.

This work was carried out with the aid of a Simon-Carves Industrial Research Scholarship, and the authors wish to place on record their sincere appreciation of the help afforded by Messrs. Simon-Carves, Ltd., not only for the financial assistance which alone rendered the work possible, but also for their public-spirited permission to publish the results.

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Iron and Steel Institute.

ON THE STRUCTURAL CONSTITUTION OF
IRON-CARBON-SILICON ALLOYS.

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(SENDAI, JAPAN).

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- § 2. The Equilibrium Diagram of the Iron-Silicon System.
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- § 4. Magnetic Analysis :
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 - (c) Alloys containing high carbon.
- § 5. Thermal Expansion at High Temperatures.
- § 6. Structural Constitution.
- § 7. Microscopic Investigation :
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 - (b) Specimens quickly cooled from the melt.
 - (c) Change of structures under heat-treatment.

§ 1. INTRODUCTION.

THE literature of the effect of silicon on the physical and mechanical properties or critical points of steel and cast iron is very extensive¹; but few papers relating to the constitutional diagram or the systematic investigation of the ternary alloys have been published. Guillet² in 1906 proposed a diagram representing the constitution of the system. Gontermann³ also studied the equilibrium diagram; but there are still some points unsettled in the region of high silicon and carbon.

The materials used in the present investigation were wrought

¹ Turner, *Journal of the Iron and Steel Institute*, 1888, No. I. p. 28; Hadfield, *ibid.*, 1889, No. II. p. 222; Arnold, *ibid.*, 1894, No. I. p. 107; Baker, *ibid.*, 1903, No. II. p. 312; Hatfield, *ibid.*, 1906, No. II. p. 157; Hague and Turner, *ibid.*, 1910, No. II. p. 72; Schols, *Metallurgie*, vii. (1910), p. 644; Paglianti, *Metallurgie*, ix. (1912), p. 217; Charpy and Cornu Thenard, *Comptes Rendus*, clvi. (1913), p. 1240; *ibid.*, clvii. (1913), p. 319; Yensen, *Univ. Illinois Bulletin*, viii. (1915), No. 12; Charpy and Cornu Thenard, *Journal of the Iron and Steel Institute*, 1915, No. I. p. 276; Andrew, *ibid.*, 1916, *Carnegie Scholarship Memoirs*, 1, &c.

² *Journal of the Iron and Steel Institute*, 1906, No. II. p. 14.

³ *Ibid.*, 1911, No. I. p. 421.

iron containing very little impurity, white pig iron, and ferro-silicon. The analyses are given in the following table :

Materials.	Carbon per Cent.	Silicon per Cent.	Manganese per Cent.	Sulphur per Cent.	Phosphorus per Cent.
Wrought iron . .	0.164	0.078	trace	0.030	0.007
White pig iron . .	3.760	0.212	0.142	0.011	0.169
Ferro-silicon . .	0.015	94.80	1.110	0.379	0.169

§ 2. THE EQUILIBRIUM DIAGRAM OF THE IRON-SILICON SYSTEM.

One of the present writers¹ proposed a revised equilibrium diagram of the iron-silicon system constructed by Professors Guertler and Tammann,² by utilising magnetic and thermal analysis, as well as microscopic observation. The diagram was further modified by Professor Guertler,³ who considers that as silicon increases the A3 point falls, and that the magnetic transformation³ taking place at a constant temperature of 450° in alloys containing 16 to 25 per cent. of silicon is due to a eutectoid transformation. The rising of the A3 point with increasing silicon has, however, been demonstrated by Messrs. Charpy and Thenard,⁴ and it is also confirmed by the present investigation, as described later on, although the magnitude of the transformation decreases as silicon increases, and in alloys containing more than 2 per cent. of silicon is not observable by thermal analysis or dilatometric means. The transformation taking place at 450° is not attributed to a eutectoid change, because the change of structure at this temperature cannot be observed even by careful microscopic investigation. From the above view the equilibrium diagram of the system is to be represented as shown in Fig. 1. In this diagram curves LK and LJ represent the range of the A3 transformation; the A2 transformation MNO in a solid solution and a magnetic transformation PQ of a compound Fe₃Si₂ at 90° are shown by dotted lines, since they are not the change of phase.⁵ The lowering of the A4 transformation with

¹ Murakami, *Sci. Rep.*, x. (1921), p. 79.

² *Zeitschrift für anorganische Chemie*, xlvii. (1905), p. 163.

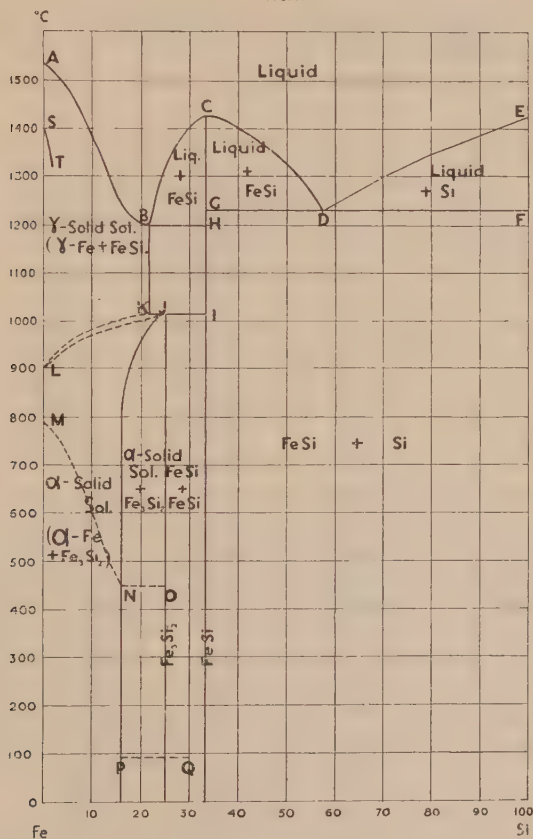
³ *Stahl und Eisen*, xlii. (1922), p. 667.

⁴ *Journal of the Iron and Steel Institute*, 1915, No. I. p. 276.

⁵ Honda, *Sci. Rep.*, iv. (1915), p. 169.

increasing silicon to 1.2 per cent. (1335° C.) has been investigated by Professor Ruer¹; curve ST is based on his result.

Fig. 1.



§ 3. THERMAL ANALYSIS.

In each experiment, 25 grammes of the materials above referred to were mixed in different proportions. The melting of the alloys was carried out by means of a porcelain tube in the Tammann furnace. Iron and white pig were at first heated to about 1500° and then the weighted mass of ferro-silicon was added. The cooling temperature of the metal was measured by means of a

¹ *Ferrum*, xi. (1914), p. 257.

platinum, platinum-rhodium thermo-element, whose hot junction was placed in a thin silica protecting tube and dipped in the molten mass.

The result of the experiments is given in Table I. and graphically in Figs. 1 to 10.

TABLE I.

Alloys No.	Composition.		Primary Crystallisation.	Eutectic Temperature.	Pearlite Formation.
	Silicon per Cent.	Carbon per Cent.			
1	2.00	0.258	1479° A4 = 1428°	...	...
2	2.14	0.462	1460° A4 = 1428°	...	702°
3	2.26	0.785	1428°	...	728°
4	2.38	1.110	1400°	...	745°
5	2.30	1.845	1331°	...	744°
6	2.08	2.720	1232°	1134°	740°
7	2.38	3.230	1170°	1137°	735°
8	2.51	3.460	1135°	1135°	746°
9	5.14	0.258	1430°	...	...
10	5.43	0.471	1409°	...	781°
11	5.48	0.595	1360°	...	782°
12	5.47	1.074	1338°	...	814°
13	5.28	1.795	1246°	1110° (?)	892°
14	5.10	2.005	1205°	1142°	885°
15	6.33	3.100	1141°	1141°	...
16	7.24	0.419	1383°	...	...
17	7.35	0.669	1346°	1172°	895°
18	7.80	0.936	1238°	1158° (1105° ?)	...
19	7.77	1.350	1170°	1134°	...
20	8.24	2.613	1153°	1153°	...
21	7.40	2.414	1152°	1152°	...
22	8.82	0.618	1303°	1168°	...
23	10.40	0.442	1297°	1150°	...
24	10.52	0.618	1250°	1165°	...
25	12.55	1.070	1170°	1170°	...
26	10.95	1.350	1170°	1170°	...
27	13.80	0.273	1315°	1173°	...
28	13.30	0.482	1250°	1185°	...
29	13.50	0.633	1202°	1185°	...
30	13.45	0.754	1193°	1188°	...
31	13.62	1.532	1185°	1185°	...
32	16.40	0.285	1238°	1191°	...
33	17.40	0.459	1193°	1193°	...
34	16.46	0.733	1194°	1194°	...
35	18.80	0.110	1213°	1193° (1150°)	...
36	18.55	0.731	1189°	1189°	...

TABLE I.—*continued.*

Alloys No.	Composition.		Primary Crystallisation.	Eutectic Temperature.	Pearlite Formation.
	Silicon per Cent.	Carbon per Cent.			
37	21.60	0.160	1200°	1200°	Formation of Fe_3Si_2
38	21.62	0.207	1203°	1203°	1013°
39	23.99	0.217	1207°	1207°	996°
40	21.00	0.235	1200°	1200°	1004°
41	0.212	4.630*			1010°
42	1.96	4.710*			
43	3.15	3.913*			
44	4.48	3.451*			
45	6.36	2.900*			
46	8.14	2.368*			
47	11.73	1.880*			
48	16.37	1.168*			
49	20.40	0.445*			
50	24.70	0.237*			

Fig. 2 shows the isothermals on the surface of crystallisation of the ternary alloys, the crosses showing the composition of the materials, and the numbers attached to them being the temperature at the beginning of the solidification of the alloys. In this figure the iron-carbon side is shown on a scale of four times as large as that of the iron-silicon side. These isothermals give a very clear idea of the form of the surface of crystallisation as silicon and carbon contents increase. The closer the isothermals lie to one another, the greater the inclination of the surface to its base.

Points marked with \odot in the diagram show the composition of the specimen, which during melting is covered with charcoal powder, exposed for thirty minutes to one hour at about 1500°, stirred several times and cast in an iron mould. Hence the carbon contents in the specimens are nearly equal to the saturated values at 1500°; the numbers marked with * in Table I. are these values. From the value, or a dotted line in Fig. 2, it can clearly be seen that the solubility of carbon gradually decreases as the silicon content increases, and in alloys containing more than 20 per cent. of silicon, the carbon content decreases to 0.4 per cent. This agrees with the fact that in adding more than 10 per

the iron-carbon system. Curves AB in these figures are the initial temperature of the primary crystallisation of iron dissolving silicon, *i.e.* liquidus curve, and A1C in Figs. 3, 4, and 5 its final temperature, *i.e.* the solidus curve. In Fig. 3 the A4 points are observable. The horizontal line CG represents a eutectic temperature of carbide and austenite containing carbon and silicon, and

FIG. 3.

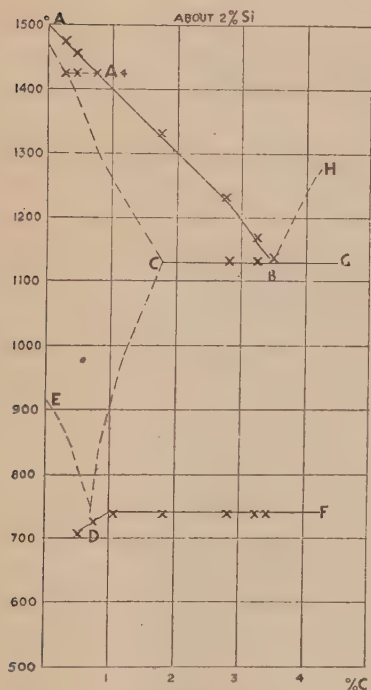
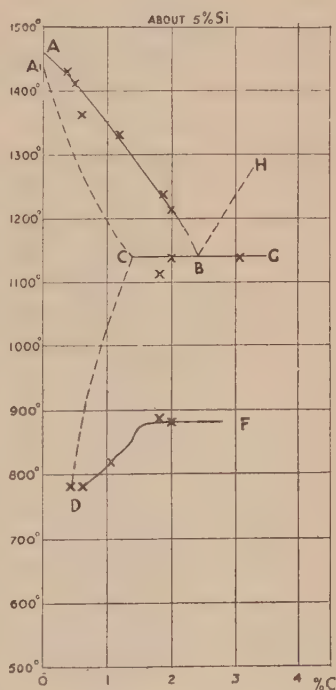


FIG. 4.

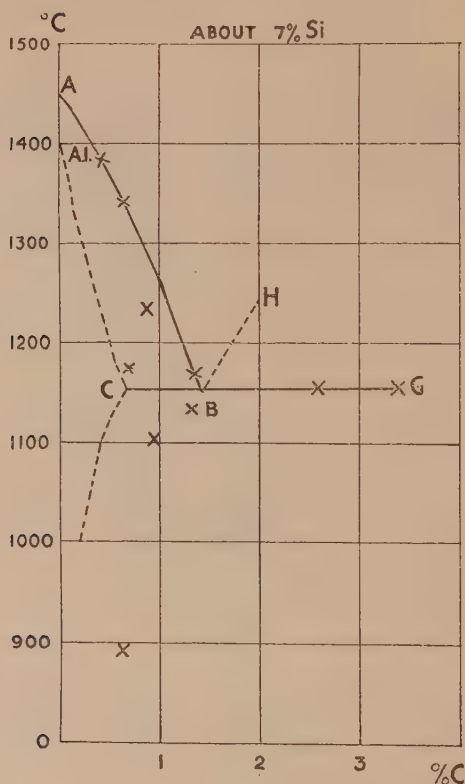


line FD, the temperature of the eutectoid separation of carbide from the austenite. The latter change is not observable in alloys containing more than 7 per cent. of silicon. Curves BH and CD are temperatures at which carbide primarily separates from the melt or the austenite; these points, however, are not observable in cooling curves, because of the smallness of heat evolution due to the separation of the carbide. Line IJ in Fig. 9 shows the temperature of the formation of compound Fe_3Si_2 .¹

¹ Murakami, *loc. cit.*

Fig. 10, A, and Fig. 10, B, show the relations between silicon content and eutectic temperature, and also carbon content at that point. The temperature gradually increases as the silicon content increases, that is, from 1130° to 1200° at 21 per cent. of silicon.

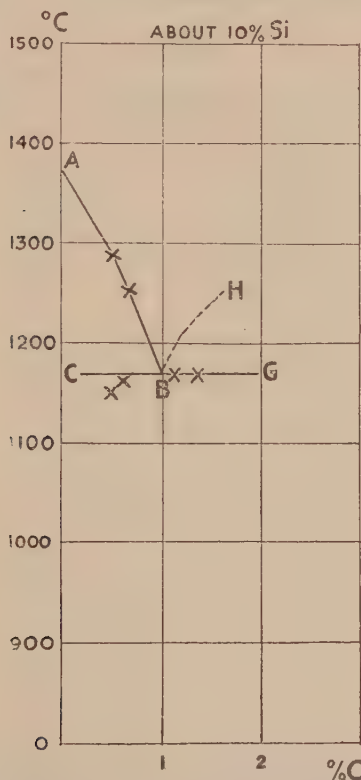
Fig. 5.



Whether the curve has a break, *i.e.* a ternary non-variant point, or not, was not confirmed. From the theoretical point of view, however, it should exist, because under the microscope a double compound which does not form a solid solution with cementite can be observed. Carbon content at the eutectic point conspicuously decreases as the silicon content increases, and in those alloys containing more than 20 per cent. of silicon it is nearly nil; that is, in these alloys the eutectic separation does not take place.

Fig. 11 represents a projection of three-dimensional model, on the basal plane, or structural diagram of the ternary alloys obtained by thermal and microscopic investigation. The plane diagrams on two sides, A'H' and A'J', of the triangle show part of

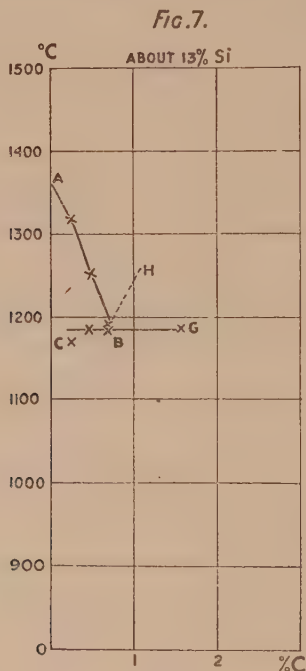
Fig. 6.



the equilibrium diagram of the binary systems of iron-carbon and iron-silicon, the scale for carbon content being much magnified. Curves B'T', C'I', and D'M in the triangle show the compositions of the eutectic point, the saturation point of carbon in austenite containing silicon, and the eutectoid point corresponding to pearlite, respectively. The curve C'I' was microscopically determined as the concentration at which the eutectic structure begins to appear as carbon increases. These three curves bend remark-

ably towards the iron corner A', showing that the carbon content of the respective point greatly decreases as the silicon content increases. The eutectoid temperature in curve D'M was further confirmed by the measurement of the expansion at high temperatures.

Gontermann¹ considers that iron carbide (Fe_3C) and iron-



silicide (FeSi) form a solid solution with each other. That is, in alloys of Fe_3C - FeSi , those containing more than 20 per cent. of silicon solidify as a solid solution and do not deposit kish; in the case of alloys with 22.3 per cent. of silicon and 2.28 per cent. of carbon no burning occurs, and the cooling curve shows only the range of crystallisation of the silico-austenite at 1211° to 1205° . In the present experiments, however, alloys containing such high silicon and carbon could not be prepared, for, by melting white pig iron with ferro-silicon, the carbon was reduced to less

¹ *Loc. cit.*

than 0.4 per cent., and the cooling curves always showed a form similar to that of the alloy containing no carbon. As a second proof of the existence of the solid solution, Gontermann states that along the curve B'I', the same phase as silico-austenite always crystallises; if this were not the case, a non-variant equilibrium should occur during crystallisation. According to

Fig. 8.

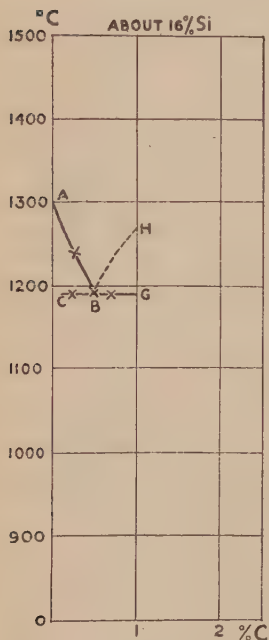
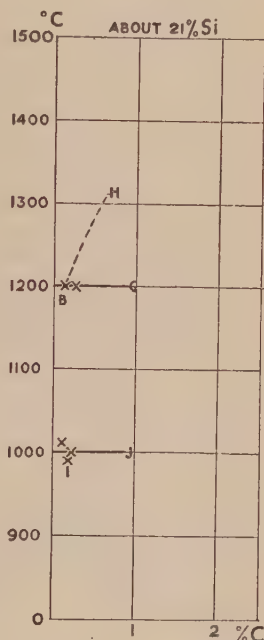


Fig. 9.



the present investigation in such high silicon alloys, carbon is slightly soluble even in the melt, and deposits as graphite during crystallisation, showing similar cooling curves, and it is very difficult to confirm the existence of the non-variant point by ordinary cooling curves. Thus, in the present experiments, there is no evidence of the existence of the solid solution of two compounds in the case of normal cooling. This is further confirmed by microscopic observation.

The crystallisation and the transformation processes of the ternary alloys can be known from the above result. In this

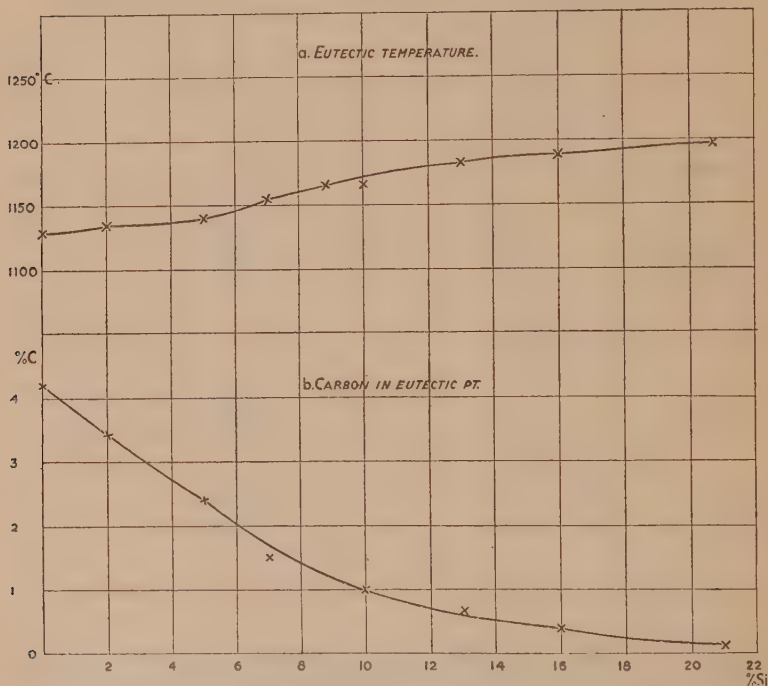
system two types of crystals separate out of the molten mass :

(1) A solid solution of iron, silicon, and carbon, termed silico-austenite.

(2) Carbide or graphite.

During crystallisation the proportions of iron, carbon, and silicon in the silico-austenite vary, and the saturated austenite and

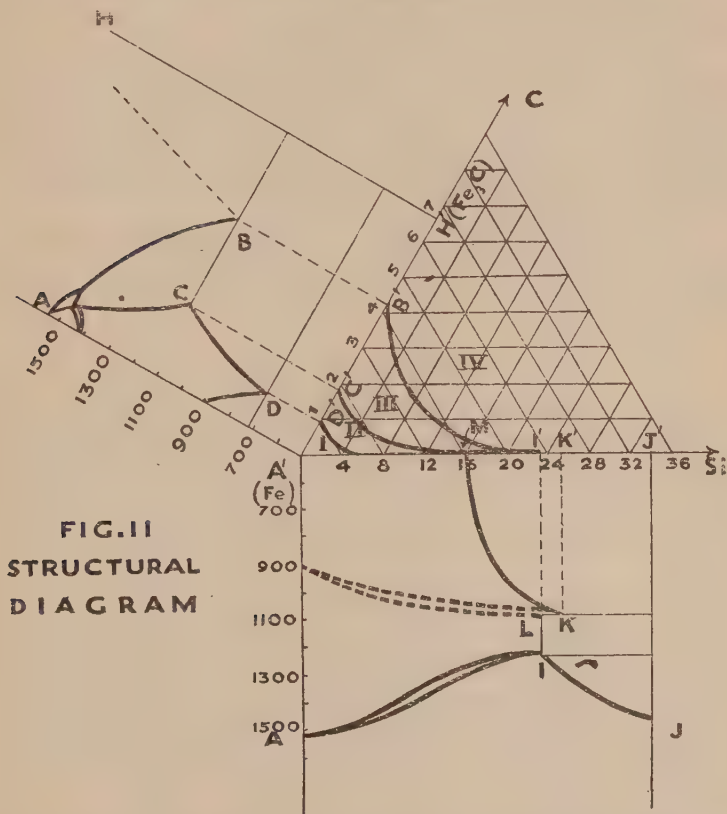
Fig. 10.



carbide (or decomposed graphite) crystallise as eutectic along curve B'I', the temperature changing with the silicon content. In further cooling, the silico-austenite deposits the silico-ferrite, i.e. ferrite containing silicon, or carbide, and at the eutectoid temperature it separates into two constituents, silico-ferrite and carbide. Hence the structure of the ternary alloys may be divided into four fields :

1. Alloys of a composition corresponding with area A'D'M

(Fig. 11) primarily solidify as silico-austenite, dissolving all silicon and carbon in solid solution; by further cooling, silico-ferrite gradually separates from the austenite, and at eutectoid temperature ferrite and carbide separate from the austenite as pearlite.



2. Alloys having the composition corresponding with area C'D'M'I' primarily solidify as austenite as in the former case; by further cooling, the carbide gradually separates from the austenite, and at eutectoid temperature the remaining austenite changes into pearlite. In alloys containing more than 16 per cent. of silicon, the separation of the compound Fe_3Si_2 from the solidified mass takes place during cooling.

3. In alloys corresponding with area B'C'I' the austenite

gradually separates from the melt, but some part solidifies as eutectic, consisting of austenite and carbide, and in a further cooling the remaining austenite changes into pearlite. In high silicon alloys containing more than 16 per cent. of silicon, the austenite gradually separates into carbide and the compound Fe_3Si_2 during cooling after solidification.

4. In alloys containing higher silicon and carbon than the composition corresponding with curve B'I', the carbide primarily separates from the melt, and at eutectic temperature suddenly solidifies as a eutectic, consisting of the austenite and carbide; the change of structure during a further cooling of the austenite is similar to that in the last case.

The formation of graphite in the alloys will be referred to later on, this being a secondary product of the carbides through decomposition.

§ 4. MAGNETIC ANALYSIS.

The magnetic analysis was made by the magnetometric method¹ as constantly used in the authors' laboratory. The test specimens were prepared by suitably alloying the materials above referred to in a graphite crucible lined with magnesia in a kryptol furnace, or in a porcelain tube in the Tammann furnace.

For the magnetic analysis, the low carbon or low silicon alloys were forged and filed in the form of a cylindrical rod 7 centimetres long and 5 millimetres thick. High carbon or high silicon alloys, which were not forgeable, were cast in an iron mould 10 centimetres long and 8 millimetres thick in bore. The silicon and carbon contents of the specimens used are shown in the following table.

Some typical magnetisation-temperature curves are given in Figs. 12 to 23. In these curves the ordinate represents the deflection δ of the magnetometer, which is proportional to the intensity of magnetisation, and the abscissa the temperature of the specimens. The rate of cooling was normal, as exemplified in a former paper,² except in the cases specially remarked on.

¹ Honda, *Sci. Rep.*, v. (1916), p. 285; Honda and Murakami, *Sci. Rep.*, vi. (1917), p. 235, &c.

² Honda and Murakami, *Sci. Rep.*, vi. (1917), p. 235.

In taking the cooling curves, the specimens were maintained at the maximum temperature for five minutes.

TABLE II.

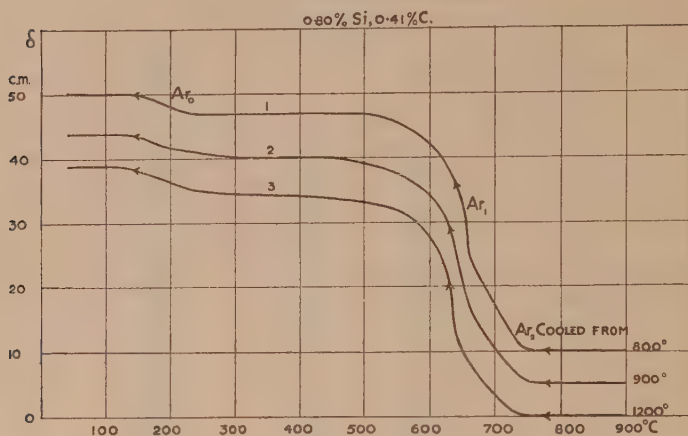
Specimen No.	Silicon per Cent.	Carbon per Cent.	Specimen No.	Silicon per Cent.	Carbon per Cent.
51	0.47	0.181	86	5.35	1.260
52	2.48	0.17	87	6.05	1.43
53	4.38	0.255	88	7.27	1.378
54	0.80	0.41	89	10.87	1.39
55	2.00	0.428	90	1.40	1.57
56	3.46	0.428	91	2.485	1.62
57	4.66	0.461	92	3.34	1.74
58	5.54	0.516	93	4.30	1.753
59	8.26	0.307	94	1.35	2.00
60	8.58	0.553	95	2.91	2.05
61	10.90	0.32	96	5.03	2.07
62	13.20	0.352	97	6.01	1.95
63	15.08	0.172	98	8.83	1.85
64	15.60	0.476	99	1.07	2.22
65	17.37	0.568	100	1.64	2.93
66	20.54	0.415	101	2.092	2.44
67	22.50	0.328	102	3.35	2.64
68	23.3	0.207	103	4.32	2.11
69	24.1	0.326	104	5.03	2.745
70	27.8	0.360	105	5.41	2.395
71	1.69	0.779	106	7.60	2.55
72	3.125	0.716	107	9.53	2.29
73	4.74	0.802	108	9.85	2.5
74	0.815	1.13	109	10.02	2.18
75	1.850	1.11	110	0.563	3.171
76	2.820	1.09	111	0.72	3.38
77	3.42	1.19	112	0.803	3.64
78	5.00	0.992	113	1.69	3.21
79	5.50	1.094	114	1.96	3.66
80	6.90	1.032	115	2.48	3.38
81	10.40	0.989	116	3.64	3.30
82	12.15	1.09	117	4.54	3.05
83	2.42	1.282	118	5.01	3.36
84	3.20	1.245	119	5.98	3.14
85	4.43	1.310	120	7.44	3.13

(a) *Alloys containing about 0.4 per Cent. of Carbon.*

Fig. 12 shows the cooling curves from different maximum temperatures for specimen No. 54. These curves are exactly similar to those of ordinary carbon steels containing no silicon; that is, three transformations occur due to Ar₂, Ar₁, and Ar₀,

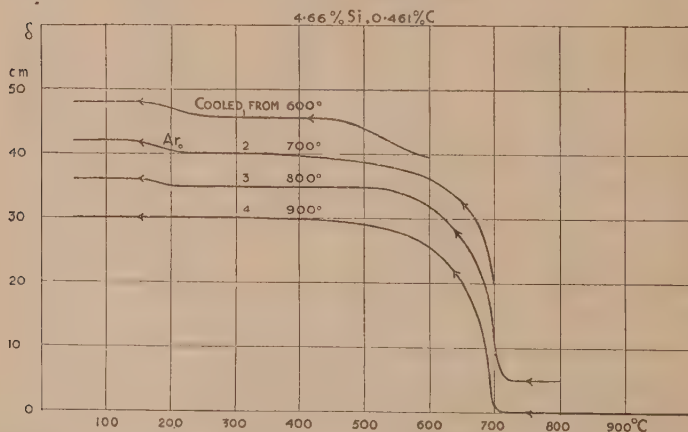
and the course of these curves hardly ever changes, although the maximum temperature is raised. This shows that in these

FIG. 12. SPECIMEN No. 54, FORGED.



alloys silicon is contained as a solid solution with iron, and the carbon as free cementite. As the silicon content increases to

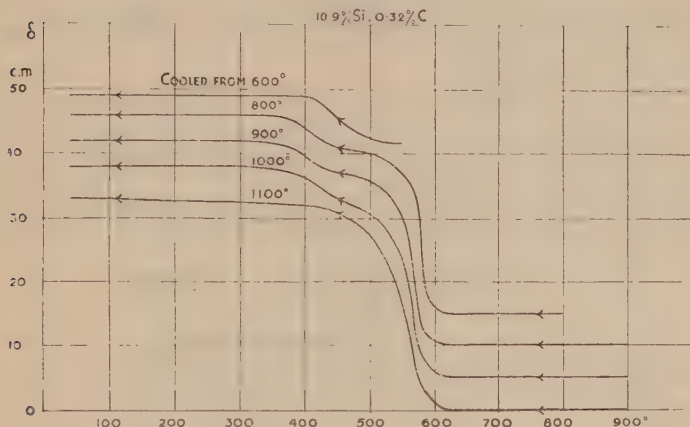
FIG. 13. SPECIMEN No 57, CAST.



3.46 per cent., the Ar_1 point gradually ascends (as shown in Figs. 12 and 13), Ar_2 and Ar_0 remaining constant. Fig. 13 shows cooling curves for specimen No. 57, containing 4.66 per cent. of

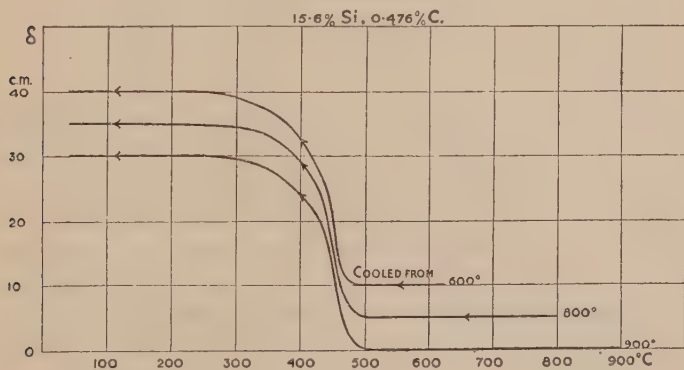
silicon, prepared by casting in an iron mould. In this case the effect of the maximum temperature is conspicuous; curve 1,

FIG. 14. SPECIMEN No. 61, CAST.



cooled from 600°, shows the Ar0 transformation and a new change beginning at 580°; but in curves 2, 3, and 4, cooled from 700°,

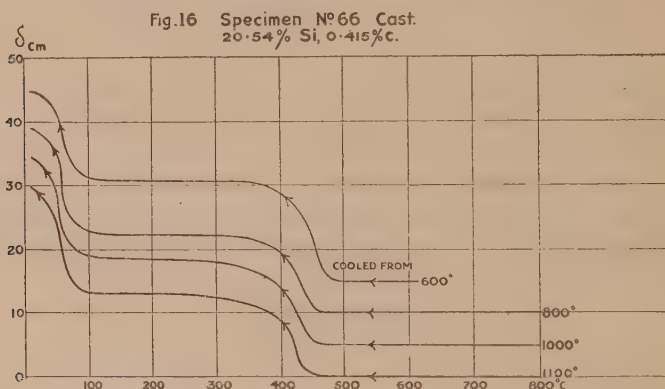
FIG. 15. SPECIMEN No. 64, CAST.



800°, or 900°, the latter change is absent, and the Ar0 change gradually decreases as the maximum temperature increases; in curve 4 it completely vanishes, owing to the decomposition of cementite. The change at 580° is not a lowered Ar1 transformation, because it is a reversible change in heating and cooling, but is due to a

solid solution consisting of silicon (silicide Fe_3Si_2), iron, and carbon (carbide), since the change is always observable in cast specimens containing these three elements, and the temperature gradually decreases as the silicon or carbon content increases. As seen from Fig. 14, this solid solution is very unstable and easily decomposes by heating.

As silicon exceeds 5.5 per cent. the A0 transformation is not observable, as shown in Fig. 14, showing the absence of the cementite, and the transformation of the solid solution gradually decreases to 450° , while the decomposition temperature during heating gradually increases; specimen No. 61 (Fig. 14) shows

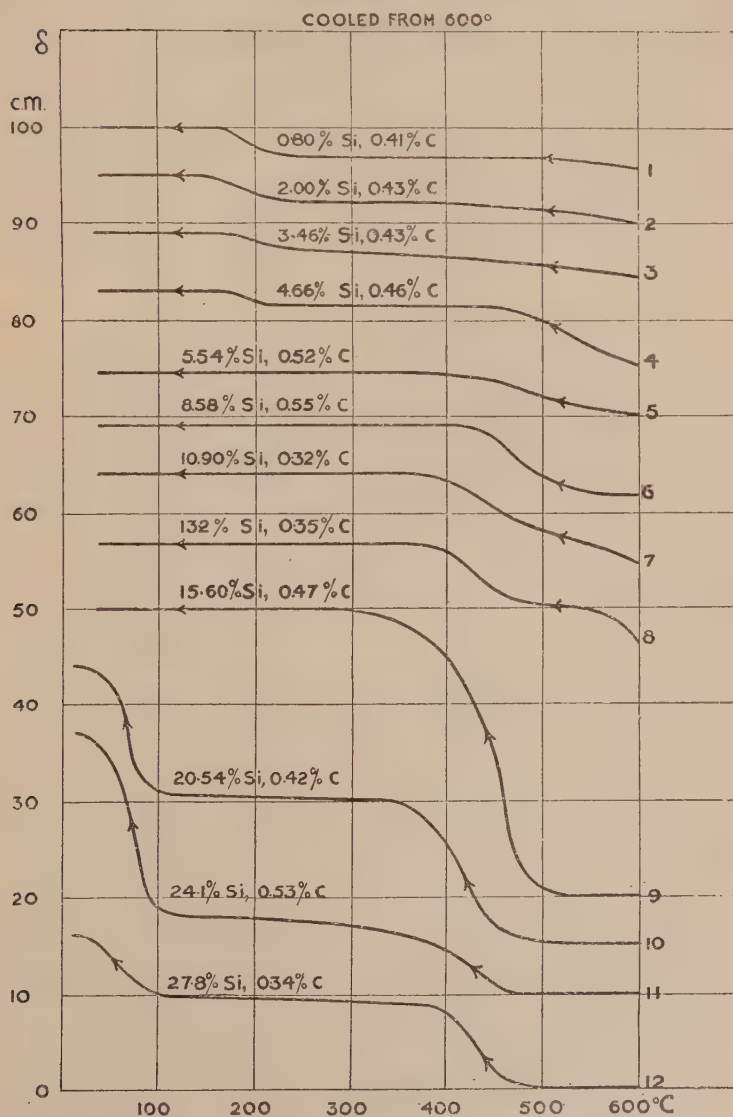


a conspicuous transformation even during cooling from 1000° . The A2 point gradually decreases with the increase of silicon content, owing to the increasing concentration of silicon (Fe_3Si_2) in iron, as shown in a previous report published by one of the present writers.¹ In the specimen containing 15.6 per cent. of silicon, the A2 change overlaps that of the solid solution (Fig. 15). If the silicon content increases beyond 16 per cent., the form of the cooling curves is exactly similar to those of the alloys containing no carbon¹; that is, a transformation occurs at 450° , due to a saturated solid solution of iron silicide (Fe_3Si_2) in iron, and another at 90° due to free silicide.¹ The change in the form of these curves as the maximum temperature is raised was fully discussed in a previous paper,¹ hence any further remarks may be here omitted.

¹ Murakami, *loc. cit.*

Figs. 17 and 18 show the cooling curves from 600° and 900°

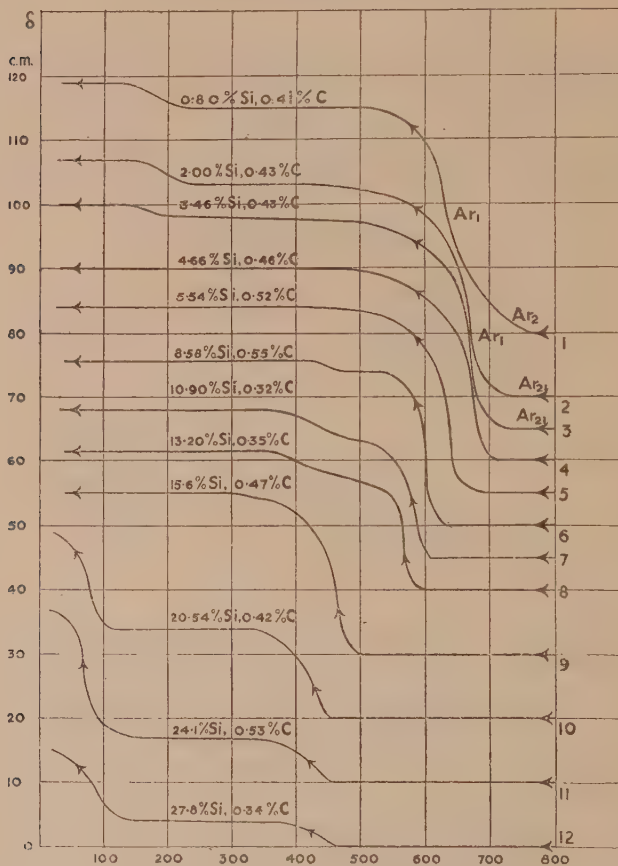
FIG. 17. SPECIMENS CONTAINING ABOUT 0.4% C.



of the specimens above referred to, put together for comparison.

From the former figure it may be concluded that : (a) The A0 transformation is observable in specimens containing less than 5.5 per cent. of silicon ; (b) the transformation at about 500°, due

FIG 18. SPECIMENS CONTAINING ABOUT 0.4% C
COOLED FROM 900°



to the solid solution of iron, silicon (Fe_3Si_2), and carbon (carbide) is seen in the alloys containing 4 to 16 per cent. of silicon ; (c) this transformation point is lowered as the silicon content increases ; (d) the cooling curves of the specimens containing more than 16 per cent. of silicon show a similar course to those of the specimens containing no carbon. From Fig. 18 the following facts may be

derived. As the silicon content increases, (a) the A0 transformation decreases in magnitude; (b) that of the solid solution increases; (c) the A2 point gradually falls up to the alloy containing 16 per cent. of silicon, but afterwards remains constant; (d) the A1 point gradually rises; this rise of the point is only observable in the alloys containing less than 4.66 per cent. of silicon, because in the alloys containing a higher percentage of silicon the A1 point increases beyond the A2 point, so that its existence cannot be detected by magnetic analysis, but by the measurement of the thermal expansion the rise of the point can clearly be observed, as shown in a later section.

(b) Alloys containing about 1 per Cent. of Carbon.

In low silicon steels the cooling curves are exactly similar to that of plain carbon steel, and the Ar1 and Ar0 transformations do not change in magnitude by cooling the specimen from different maximum temperatures. As the silicon content increases, the amount of the A0 transformation decreases as the maximum temperature increases from 650° to 1000° (Fig. 19, curves 1, 2, and 3), owing to the decomposition of cementite during cooling from a high temperature. The amount of free cementite depends on the rate of cooling, as shown in curves 4 to 8; that is, the A0 transformation is equally large in magnitude for three different maximum temperatures, provided the cooling is quick, while in the curve slowly cooled from 900° the A0 change is not observable.

As the silicon content further increases, and in addition to the A0 transformation, another transformation—that of the solid solution—appears at 550° to 450°. This change, however, readily disappears during heating beyond 850°. In specimens containing more than 5.5 per cent. of silicon the A0 change is not observable; on the contrary, that of the solid solution becomes conspicuous (Fig. 20), and its decomposition temperature gradually increases with increasing silicon, as remarked in the foregoing series.

(c) Alloys containing High Carbon.

In these alloys the A0 transformation, or that of the solid solution at 550° to 450°, is very conspicuous, owing to high carbon

FIG. 19. SPECIMEN No 75, FORGED.

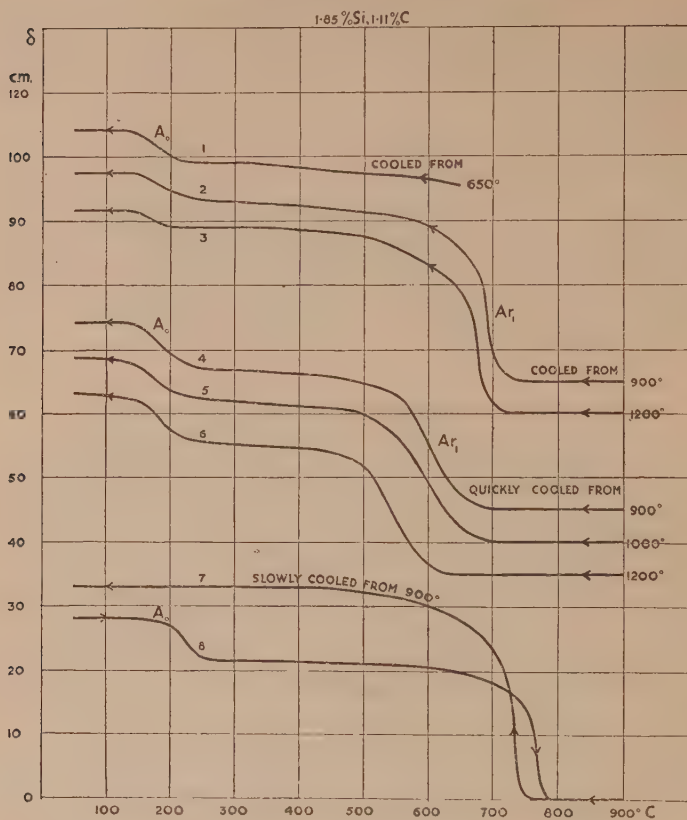
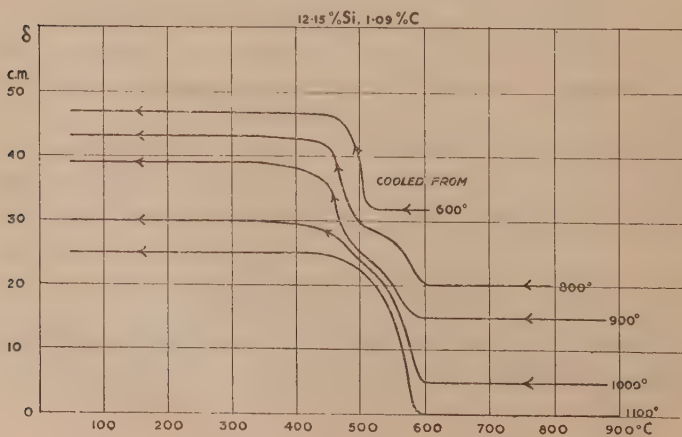
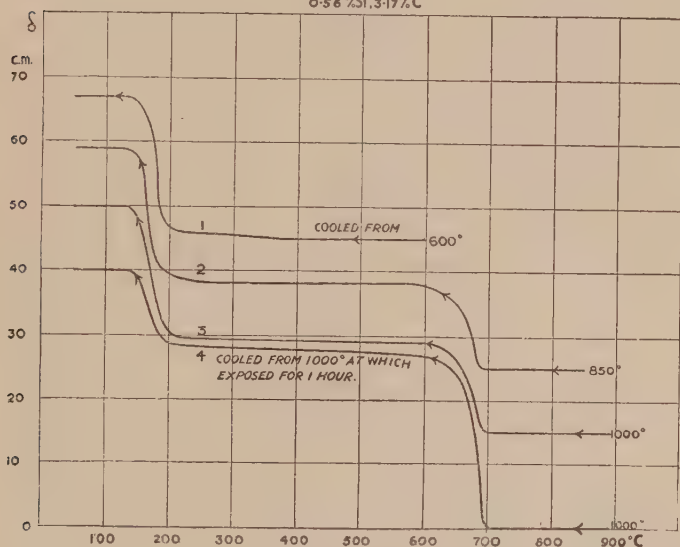


FIG 20. SPECIMEN No 82.



content. The latter change is seen in the specimens containing more than 0.8 per cent. of silicon, while in specimen No. 110, containing 0.56 per cent. of silicon, it is absent (Fig. 21). As the silicon increases, the disappearance of the A0 transformation during heating or cooling becomes more marked. Thus, in specimen No. 110 (Fig. 21), the decrease of A0 transformation is small even on heating the specimen at 1000° for one hour (curve 4); in

FIG. 21. SPECIMEN No 110.
0.56%Si, 3.17%C



specimen No. 112 (Fig. 22) it is very conspicuous in a normal cooling after an exposure at 1000° for five minutes (curve 4).

As the silicon further increases, the decomposition temperature of cementite during reheating gradually falls; that is, in specimen No. 115, containing 2.48 per cent. of silicon, this temperature is 900°; in specimens Nos. 117 and 105, containing respectively 4.54 and 5.41 per cent. of silicon, 800° (Fig. 23). On the other hand, as the silicon content increases, the transformation due to the solid solution persists to a higher temperature; thus in low silicon alloys it disappears during heating to 800° to 900°, but in specimen No. 107, containing 9.53 per cent. of silicon, it is still observable in the cooling curve from 900°.

The heating curves were also observed and recorded during

FIG. 22. SPECIMEN No 112.

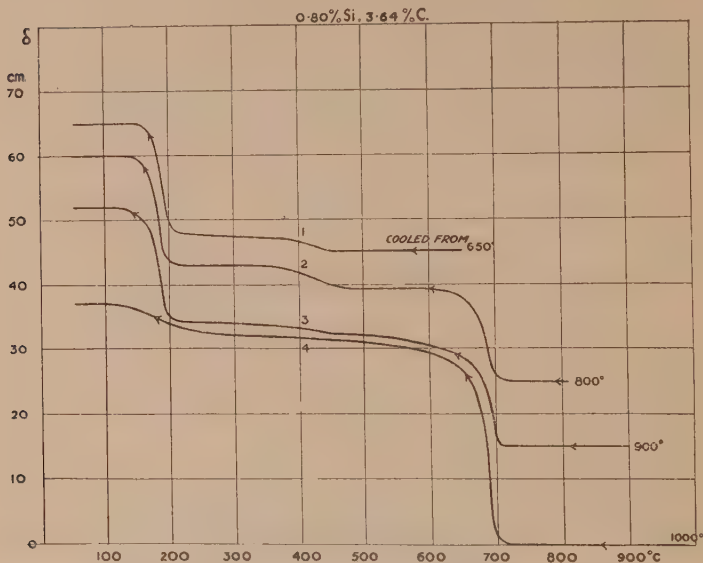
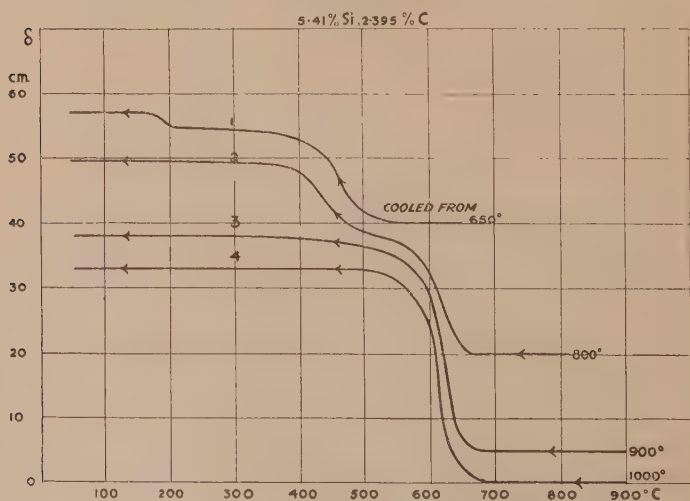


FIG. 23. SPECIMEN No 105



every heating in the case of all specimens. The heating curves have a form similar to the preceding cooling curve, some tempera-

ture hysteresis existing between the heating and cooling curves in the range of transformation.

§ 5. THERMAL EXPANSION AT HIGH TEMPERATURES.

Thermal analysis is not convenient for determining the exact temperature of the transformations; nor is magnetic analysis a very easy method for this purpose if the transformation takes place above the A2 point, because, in this case, a torsion balance of high sensibility must be employed. For the same purposes, measurement of thermal expansion at high temperatures is, however, preferable; hence the thermal expansion of some specimens were in this case measured. The measurement was made *in vacuo* with the arrangement constantly used in the author's laboratory.¹ The specimens used were cylindrical rods 20 centimetres long and 5 to 6 millimetres thick. These alloys containing high carbon, being not forgeable, were prepared by casting the molten metal in an iron or asbestos mould, and afterwards grinding up. The asbestos mould was suitable for preparing slowly cooled specimens.

The results of measurement are given in Figs. 24 to 27. The ordinate represents the deflection of the scale, which is proportional to the elongation of the specimens, and the abscissa its temperature. The temperature-expansion curves change considerably with heat-treatment. The curves shown in these figures are those of samples previously heated to 900° and cooled at the normal rate. To avoid the overlapping of the curves, they are drawn superposed upon one another. Unless specially qualified, these curves were obtained during the normal heating and cooling, their rate being nearly equal to the normal cooling in the magnetic analysis.

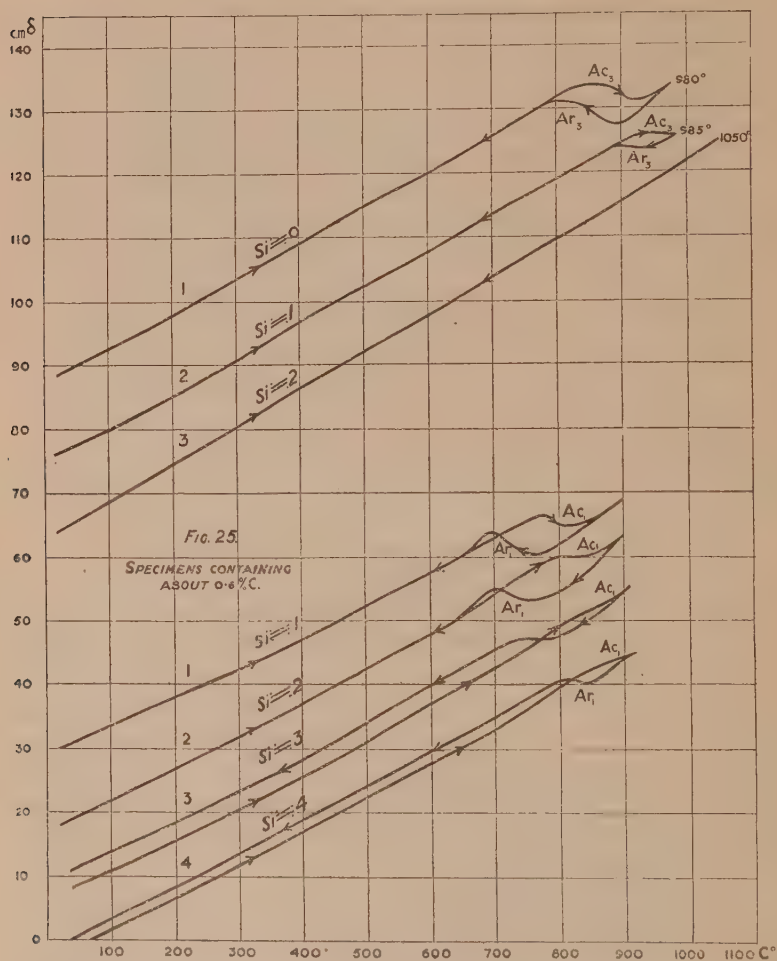
Fig. 24 shows the dilatation-temperature curves for specimens containing no carbon. The abnormal changes in curves 1 and 2 are attributable to the A3 transformation. From these curves it is seen that as silicon increases the transformation point rises and its magnitude decreases, but it is not observable in specimens containing more than 2 per cent. of silicon.

The heating and cooling curves for the specimens containing

¹ Honda, *Sci. Rep.*, vi. (1917), p. 203.

about 0.6 per cent. of carbon are shown in Fig. 25. The abrupt changes in these curves are mainly attributable to the A1 trans-

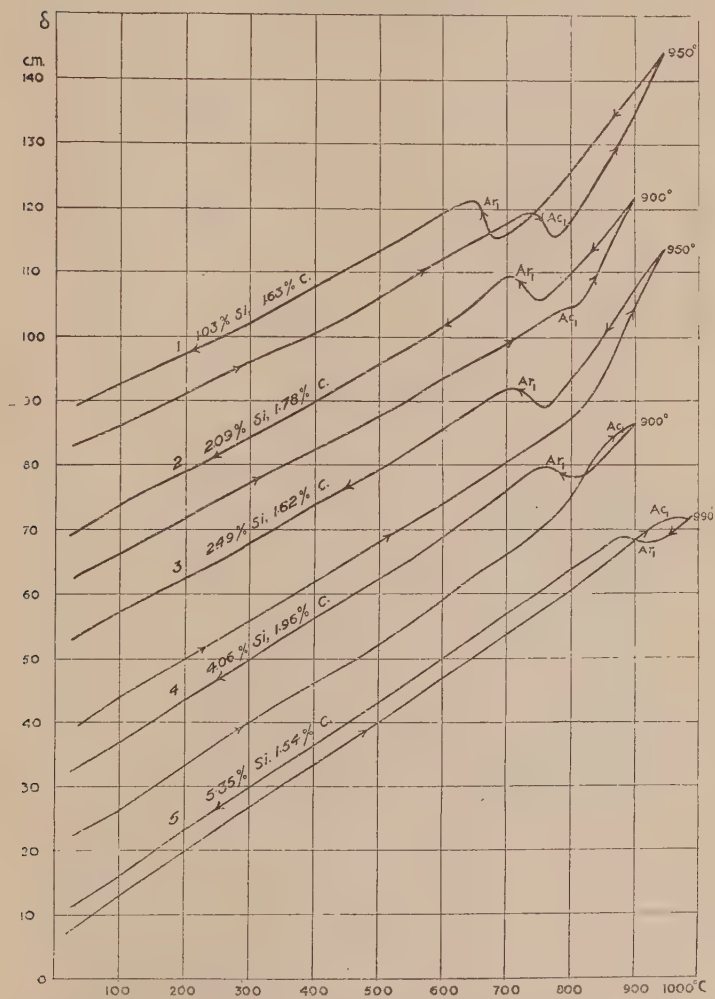
FIG. 24. SPECIMENS CONTAINING NO CARBON.



formation, since the A3 change is not conspicuous if the silicon exceed 2 per cent., as seen from the above. This transformation temperature rises and its magnitude decreases as silicon increases. The deviations of the heating and cooling curves 3 and 4 from

each other are due to the growth of the alloys during heating, as in the case of cast iron.

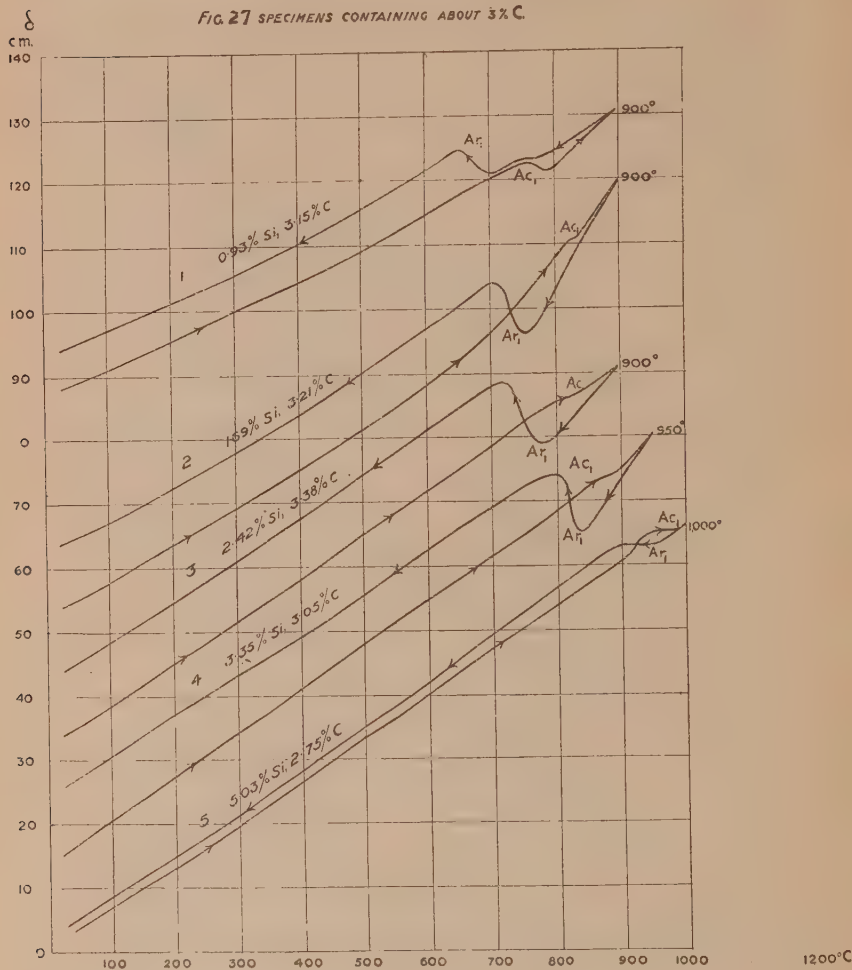
Fig. 26 SPECIMENS CONTAINING ABOUT 1.7% C.



In the curves in Figs. 26 and 27 the growth is very conspicuous, the magnitude of the Ar_1 transformation being always greater than that of the Ac_1 change. The explanation of this

large growth is given in Mr. Kikuta's paper.¹ The rising of the transformation point and the decrease of its magnitude with increasing silicon are also observable in these cases.

FIG. 27 SPECIMENS CONTAINING ABOUT 3% C.



§ 6. STRUCTURAL CONSTITUTION.

According to Dr. Stead, a double compound, silico-carbide, exists in iron-carbon-silicon alloys, prepared by quick cooling.

¹ T. Kikuta, *Sci. Rep.*, xi. (1922), p. 1.

In the present investigation the authors found likewise a non-magnetic, unstable double compound under the microscope. A new magnetic transformation at about 500° , however, cannot be attributed to a definite double compound, as previously stated. Actually, in cast specimens having a change at about 500° , no crystal corresponding to the change can be observed under the microscope with a dendritic structure; in a slowly cooled specimen the non-magnetic crystal is observable, showing no change at about 500° , provided carbon content is not large. Hence the authors hold the view that the magnetic change is due to the solid solution of iron, silicon (Fe_3Si_2), and carbon, from which the non-magnetic double compound may separate, though high carbon alloys always deposit graphite in a slow cooling.

The structural constitution of the iron-carbon-silicon alloys can be deduced from the results of magnetic analysis and microscopic observation. In the magnetic analysis, most of the specimens were prepared by casting them in an iron mould. The low silicon and low carbon alloys were, however, forged. The constitution in the cast condition of these alloys can be deduced from the cooling curves from 650° , during which the constitution does not change. If the maximum temperature be raised, or the specimens be annealed at high temperature, or slowly cooled from the melt, the cooling curves have a different form, as do those of the specimens cooled from 650° . This shows that the constitution in the cast condition is totally different from that in the annealed or equilibrium condition.

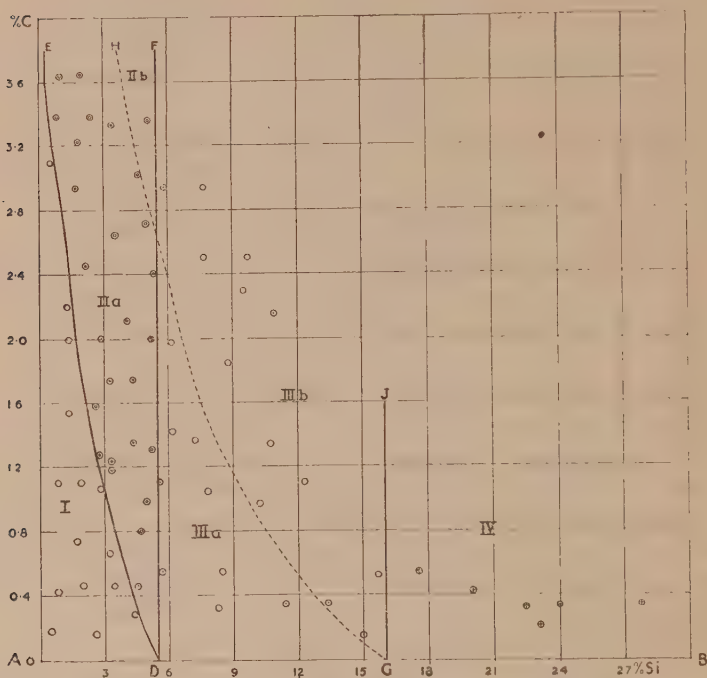
The constitution in the cast or quickly cooled condition will first be considered. According to the magnetic analysis, all the alloys which were examined may be classified into six groups, determined by the cooling curves from 650° .

- (i) Alloys having two transformations at about 700° and 200° .
- (ii) Alloys having three transformations at about 700° , 500° , and 200° .
- (iii) Alloys having two transformations at about 650° to 500° and 500° .
- (iv) Alloys having two transformations at 450° and 90° .

Fig. 28 shows the constitutional diagram. The ordinate

represents the carbon content, and the abscissa the silicon content of the alloys. Marks \circ , \odot , \ominus , and \oplus show the composition of the alloys belonging respectively to the fields (i), (ii), (iii), and

Fig. 28

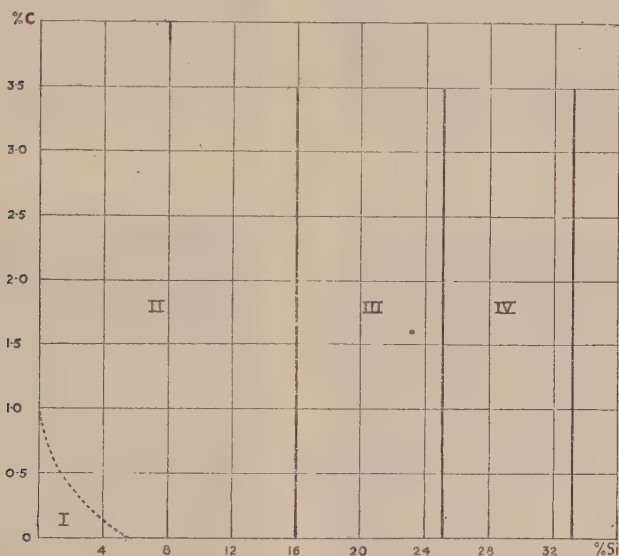


(iv) above referred to. Lines DE, DF, and GJ are the boundaries between these fields.

From the fact that cementite and silicide (Fe_3Si_2) have their transformations at 200° and 90° respectively ; that the transformation point of the solid solution of silicide (Fe_3Si_2) in iron falls from 780° to 450° , as the concentration increases ; and that the ternary solid solution of carbon and Fe_3Si_2 in iron has its transformation at 580° to 450° , according to its concentration, the presence or absence of these phases in the alloys belonging to the above field can be readily detected. According to the microscopic investigation, the alloys containing high carbon and high silicon always contain some free graphite, although its content varies with the

composition ; that is, as silicon increases, the amount of graphite increases, and in the alloys containing more than 16 per cent. of silicon the dissolved carbon is almost nil. The boundary of the alloys in which decomposed graphite appears is shown in dotted line GH, each of the fields II and III being thus divided into two

Fig. 29



parts. Hence the constituents in the cast alloys belonging to fields I, IIa, IIb, IIIa, IIIb, and IV are as follows :

- I. $[\text{Fe} + \text{Fe}_3\text{Si}_2] + [\text{Fe}_3\text{C}]$
- IIa. $[\text{Fe} + \text{Fe}_3\text{Si}_2] + [\text{Fe}_3\text{C}] + [\text{Fe} + \text{Fe}_3\text{Si}_2 + \text{C}]$
- IIb. $[\text{Fe} + \text{Fe}_3\text{Si}_2] + [\text{Fe}_3\text{C}] + [\text{Fe} + \text{Fe}_3\text{Si}_2 + \text{C}] + [\text{C}]$
- IIIa. $[\text{Fe} + \text{Fe}_3\text{Si}_2] + [\text{Fe} + \text{Fe}_3\text{Si}_2 + \text{C}]$
- IIIb. $[\text{Fe} + \text{Fe}_3\text{Si}_2] + [\text{Fe} + \text{Fe}_3\text{Si}_2 + \text{C}] + [\text{C}]$
- IV. $[\text{Fe} + \text{Fe}_3\text{Si}_2] + [\text{Fe}_3\text{Si}_2] + [\text{C}]$

The bracket [] shows a single phase consisting of the substances enclosed by it. The bending of lines DE and GH towards the ordinate indicates that the amount of free cementite or dissolved carbon decreases as silicon increases. The fact that line GI is vertical shows that the amount of free silicide (Fe_3Si_2) or its saturated solid solution in iron is not affected by the addition of carbon, provided the silicon content is constant, the whole

carbon appearing in a free state. Similarly, line DF is nearly vertical, showing that all the cementite is decomposed in the alloys containing more than 5.5 per cent. of silicon, irrespective of carbon content. The effect of further increasing the cooling rate was also tested ; that is, specimens Nos. 87 and 119 having a composition approaching to the line DF were remelted with carbon powder, and cast in an iron mould of a larger mass and a smaller bore than that previously used. Magnetically examined, the A0 transformation was not observable, showing that the cementite is not formed even by further increased cooling, provided the silicon exceeds 5.5 per cent.

The structural constitution of the alloys in the annealed state, or in the equilibrium state, can be deduced from these curves recorded during slow cooling from a temperature above 900°, after a long exposure at that temperature. These curves were not recorded for all specimens, because the curves during cooling at the normal rate from 1000° to 1200°, after an exposure of five minutes, showed a similar form to those of the annealed ones. Hence the structural constitution in the annealed state may be deduced from these curves, cooled from 1000° to 1200°, as described in the foregoing section of the magnetic analysis. In these curves, the transformations due to the cementite and the solid solution of iron, silicon, and carbon are not observable, but the A2 transformation only is present ; that is, the course of the curves is exactly similar to that of the curves for the specimens containing silicon and no carbon, with the exception of the low silicon and low carbon alloys, in which the A0 transformation is observable. From the microstructure of the annealed specimens, it is seen that carbon exists in a free state. Hence the structural constitution of these alloys can be classified into the following four groups :

- I. $[\text{Fe} + \text{Fe}_3\text{Si}_2] + [\text{Fe}_3\text{C}]$
- II. $[\text{Fe} + \text{Fe}_3\text{Si}_2] + [\text{C}]$
- III. $[\text{Fe} + \text{Fe}_3\text{Si}_2] + [\text{Fe}_3\text{Si}_2] + [\text{C}]$
- IV. $[\text{Fe}_3\text{Si}_2] + [\text{FeSi}] + [\text{C}]$

Fig. 29 shows the constitutional diagram of the alloys in the annealed state. Cementite in the alloys belonging to group I. does not readily decompose by being annealed at high temperatures, since it dissolves at a temperature above the A1 point into

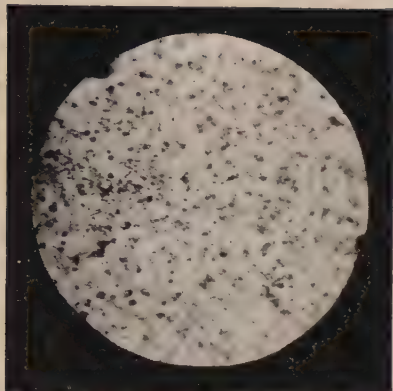


FIG. 30. 7.24% Si, 0.419% C.
Normally cooled from melt. $\times 80$.

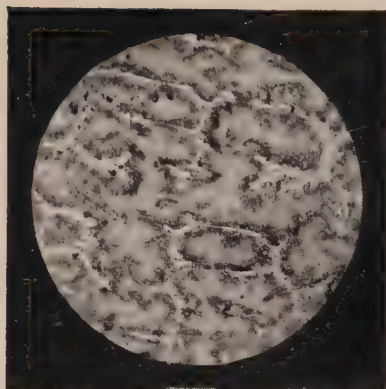


FIG. 31. 2.3% Si, 1.845% C.
Normally cooled from melt. $\times 80$.

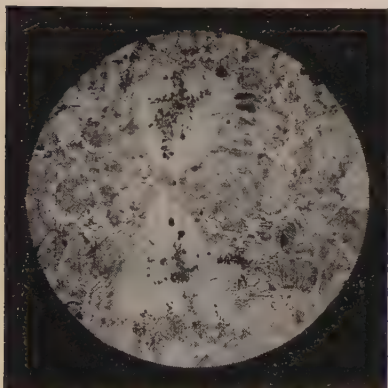


FIG. 32. 7.57% Si, 1.148% C.
Normally cooled from melt. $\times 80$.

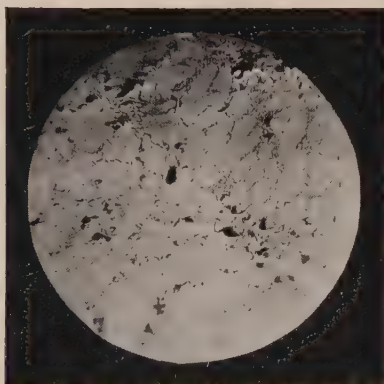


FIG. 33. 10.4% Si, 0.442% C.
Normally cooled from melt. $\times 80$.



FIG. 34. 6.33% Si, 3.10% C.
Normally cooled from melt. $\times 80$.

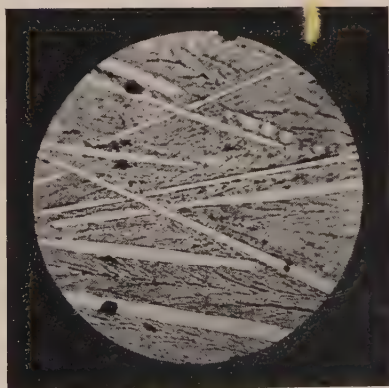


FIG. 35. 0.93% Si, 4.54% C. Cast in
iron mould. $\times 80$.

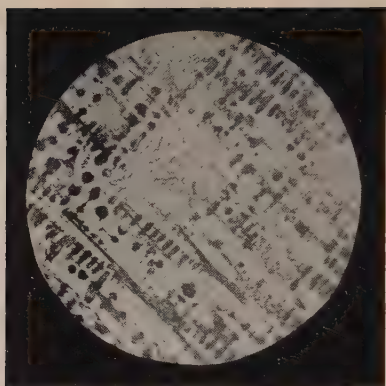


FIG. 36. 5.63% Si, 1.80% C. Cast in iron mould. $\times 220$.

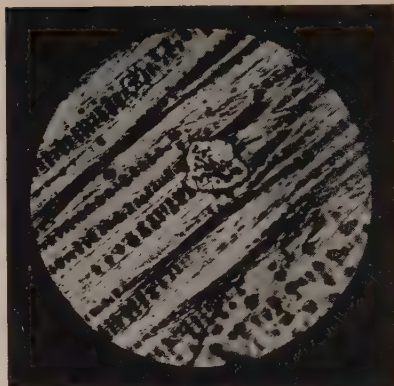


FIG. 37. 5.38% Si, 2.165% C. Cast in iron mould. $\times 220$.

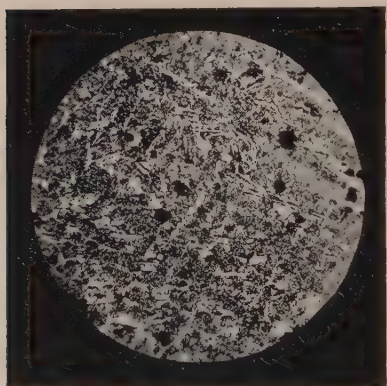


FIG. 38. 1.29% Si, 2.686% C. Cast, annealed at 900° for 40 min. $\times 80$.

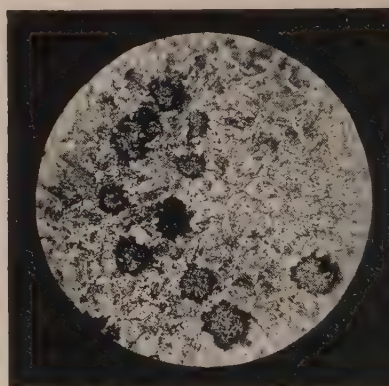


FIG. 39. Same specimen. Cast, annealed at 900° for 130 min. $\times 80$.



FIG. 40. Gray pig. 1.54% Si, 3.28% C, annealed at 900° for 5 min. $\times 80$.



FIG. 41. Same specimen. Annealed at 900° for 1 hour. $\times 80$.

austenite. If the cementite be annealed at a temperature below the A1 point for a sufficiently long time it will completely vanish, and hence in the completely annealed state group I. will be contained in group II.

According to Guillet's diagram,¹ silicon steels are divided into three groups—*i.e.* (1) pearlitic steels, (2) pearlitic and graphitic steels, (3) graphitic steels; the lines separating these different zones are very nearly parallel to the carbon axis, showing that the constitution of silicon steels is practically independent of their carbon content. According to the result of the present investigation, the field of cementite or pearlite is, however, largely influenced by carbon and silicon contents in the alloys as well as by the rate of cooling from the melt. That is, in low silicon steels belonging to the pearlitic group of Guillet's diagram, graphite flakes are easily produced, if carbon is high, even by a rapid cooling. On the other hand, in high silicon steels belonging to the graphitic group, no graphite is observable even on a slow cooling, provided the amount of the carbon is small.

§ 7. MICROSCOPIC INVESTIGATION.

The microstructures of the alloys used in the present investigation were all carefully examined after casting, thermal and magnetic analyses, or various heat-treatments. As the etching reagent, an alcoholic solution of picric or nitric acid was used for the low silicon alloys, and an aqueous solution of nitric acid or aqua regia for the high silicon alloys.

(a) *Specimens normally cooled from the Melt.*

The structure of the alloys subjected to the thermal analysis before referred to—*i.e.* the alloys cooled at the normal rate from the melt—will first be described. The results of microscopic investigation completely agree with the diagram in Fig. 11 deduced from the result of thermal analysis.

Alloys belonging to group I. in Fig. 11 consist of pearlite and ferrite dissolving silicon or silico-ferrite as plain hypoeutectoid steels, and those in group II. pearlite and carbide primarily

¹ *Loc. cit.*

separated from austenite as plain hypereutectoid steels. In alloys containing 5 to 8 per cent. of silicon we see needle-shaped crystals of carbide, and lamellar structure can scarcely be observable in these alloys, as shown in Fig. 30. It has been seen from the thermal analysis that the carbon content in eutectoid decreases as silicon increases. This fact agrees completely with the result of the microscopic investigation; that is, specimens containing some silicon are hypereutectoid, although the carbon content is less than 0.9 per cent.; and the alloy containing 7.24 per cent. of silicon contains primary carbide in the form of acicular crystals with only 0.419 per cent. of carbon (Fig. 30). According to the magnetic analysis, this specimen does not show the A0 transformation, showing that this carbide is not plain cementite, but a non-magnetic double compound.

The alloys belonging to group III. consist of pearlite and eutectic carbide, as shown in Fig. 31. The eutectic is formed from carbide and silico-austenite during cooling from the melt, and the pearlite by the decomposition of the austenite. As the silicon content increases, some graphite appears during the normal cooling. In Fig. 32 a partially graphitised part can be seen, and in Fig. 33 the whole carbide is graphitised.

In alloys having the compositions corresponding with line B'I', flaky graphites are distributed in the whole area.

If the silicon and carbon contents further increase, besides flaky graphites large straight graphites appear, as shown in Fig. 34. As has already been remarked in a former paper,¹ these graphites are considered to be a decomposition product of large primarily separated needle-shaped carbides. As the silicon content exceeds 16 per cent. the solubility of carbon becomes very small even in the melt, and is practically nil in silico-austenite. In these alloys graphite always appears in the form of thin needle crystals.

(b) *Specimens quickly cooled from the Melt.*

The structure of the alloys quickly cooled or cast in iron mould from the melt for the magnetic analysis, show a similar structure to those normally cooled from the melt, though the structure is always fine, provided the silicon and carbon contents are low.

¹ *Sci. Rep.*, x. (1921), p. 273.

As the carbon content increases, the ledeburite and sorbite (changed from austenite) are observable, as in white pig iron, and by further increasing the carbon long acicular primary cementites appear (Fig. 35). The existence of these primary cementites becomes more difficult with increasing silicon, even in the specimen saturated with carbon during melting. In order to examine the relation between silicon content and the form of primary crystals, the following experiments were made on specimens Nos. 107, 113, 83, 56, 117, 119, and 107, containing respectively 0.953, 1.69, 2.42, 3.46, 4.54, 5.98, and 9.53 per cent. of silicon. These specimens were melted in the Tammann furnace, granulate gas carbon added, and after an exposure for thirty minutes at about 1500° , cast in the iron mould. In the specimen containing no silicon, large primary cementite crystals are observable; as the silicon increases the crystals decrease in size, and in the specimens containing more than 3.64 per cent. of silicon, no primary crystal of cementite is observable. On the other hand, large straight graphites appear in high silicon alloys during the normal cooling, as shown in Fig. 34.

In high silicon alloys quickly cooled from the melt, a carbide-like constituent appears in the microstructure. According to the magnetic analysis, these specimens show a conspicuous change at about 500° , but no A0 transformation, showing that this constituent is not plain cementite, but the solid solution of iron, carbon, and silicon, as previously described. In fact, there could not be observed any special crystal in specimens having this transformation; there was always a dendritic structure. If the silicon content be not large, a special constituent, probably non-magnetic carbide, begins to appear during quick cooling in the iron mould. This is shown in Fig. 36, where special angular crystals have separated from some parts of the dendrite. As the silicon and carbon contents further increase, graphite appears even on a quick cooling (Fig. 37). In the alloys containing more than 16 per cent. of silicon the solid solution is hardly present, the whole carbon existing as graphite.

(c) Change of Structures under Heat-Treatment.

In the magnetic analysis it has been seen that the iron-carbon-silicon alloys show different cooling curves for the cast

and annealed specimens ; that is, the transformations due to cementite, and the solid solution in the specimens prepared by casting, disappear when annealed at high temperatures. In order to study the change microscopically, many experiments were made. The mode of graphitisation during cooling or annealing is similar for different alloys, but the rate of graphitisation differs with the composition and annealing temperature.

For the purpose of studying the effect of the cooling rate on the structure the molten mass was cast in an iron mould, which was heated to different temperatures by means of an electric furnace, and allowed to cool. By this means different structures were obtained ; that is, if the mould were at a low temperature and the silicon content small, a fine structure was obtained, carbon being present as carbide or its solid solution, while, in the alloys cast in the mould heated to a high temperature, the flaky graphites are observable, their size increasing with the mould temperature.

Figs. 38 and 39 show the progress of graphitisation in a specimen containing 1.29 per cent. of silicon and 2.68 per cent. of carbon cast in the iron mould and annealed at 900°. The annealing of the specimen was made in an electric furnace, enclosed tightly in a porcelain tube with carbon powder, and after the required time of annealing, the tube containing the specimen was allowed to cool in the air.

In Fig. 38, for the specimen containing 1.29 per cent. of silicon, cast and annealed at 900° for forty minutes, can be seen some graphite spots and much carbide undecomposed in the ground of pearlite. As the annealing proceeds, the graphite spots become bigger and the carbide decreases, and in the specimen annealed for 130 minutes all the ledeburite carbide was decomposed (Fig. 39). If the annealing further proceeds, pearlite and graphite surrounded by ferrite are observable, but a complete graphitisation can only be obtained by a very prolonged heating, as in the case of malleable cast iron. According to the magnetic analysis, this specimen does not show the A0 transformation ; hence the carbide consisting of pearlite is not the cementite, but probably a non-magnetic double compound.

Figs. 40 and 41 show the change of structure of a commercial grey pig iron containing 1.54 per cent. of silicon and 3.28 per cent.

of carbon (manganese, 0.279 per cent.; phosphorus, 0.293 per cent.; sulphur, 0.095 per cent.) by annealing. The pig iron as received contains flaky graphite and pearlite. On heating to 700° (below A1 point), the structure does not change. If it is annealed at 900° for five minutes, ferrite is produced round the graphite, as shown in Fig. 40. As the annealing further proceeds, the pearlitic area gradually decreases, and at last we obtain a structure consisting of flaky graphites and ferrite, as shown in Fig. 41. The same structures are also obtainable by different degrees of slow cooling. The form of graphite differs according to the condition of formation; *i.e.*, in the case of annealing, the graphite appears as spots or irregular worm-like forms, while that produced in the solidifying range during cooling from the melt is straight or flaky.

From the microstructures showing the progress of graphitisation, we can infer that the graphite present in the alloys is the secondary product decomposed of carbide and not a primary one directly separated from the melt or austenite, as in the case of iron-carbon alloys containing no silicon.¹ That the slower the rate of cooling the bigger the graphite flakes, and that as the annealing proceeds the spotted or worm-like graphite becomes larger and carbide decreases in amount, are attributable to the aggregations of graphite particles produced by decomposition of the cementite by the catalytic action of carbon monoxide or dioxide. As is seen from the result of the thermal analysis, the solubility of carbide in the melt or austenite decreases, and the eutectic and eutectoid temperatures rise as the silicon content increases. The double compound, probably consisting of cementite and iron silicide, is very unstable and easily decomposable. These facts favour the formation of graphite in the iron-carbon-silicon alloys; that is, the carbide is set free at higher temperatures than in those containing no silicon, and this accelerates the decomposition of the compound.

SUMMARY.

The result of the present investigation may be summarised as follows:

1. By utilising thermal and magnetic analyses and micro-

¹ *Sci. Rep.*, x. (1921), p. 273.

scopic observation, the iron-carbon-silicon alloys containing less than 30 per cent. of silicon and 4 per cent. of carbon have been systematically investigated, and a structural and constitutional diagram has been obtained; the process of crystallisation and transformation of the ternary alloys as well as the change of structure under heat-treatment have also been studied.

2. In this system a non-magnetic double compound, or silico-carbide, probably consisting of cementite and iron silicide, is found. This compound is very unstable and easily decomposes to form graphite.

3. Plain cementite is also found in this system, provided the silicon content be less than 5.5 per cent. If the silicon further increase, it is not observable, irrespective of carbon content or rate of cooling. At room temperature, this carbide does not form a solid solution with the double compound or silicide.

4. The solubility of carbides (cementite or double compound) in the melt decreases as silicon increases, and in alloys containing more than 20 per cent. of silicon it is about 0.3 per cent. at 1500°.

5. During cooling from the melt, a silico-austenite or carbide, which easily decomposes to form graphite, primarily separates, and at a certain temperature these two form a eutectic, provided the composition of silicon and carbide exceeds a certain limit. The eutectic point gradually rises from 1130° to 1200°, and its composition of carbon decreases from 4.3 per cent. to 0 as silicon increases.

6. By a further cooling the silico-austenite sets free the silico-ferrite or carbide, which easily decomposes to form graphite, and at a certain temperature these two form a pearlite. The eutectoid point gradually rises, and its concentration of carbon decreases as silicon increases; in alloys containing more than 7 per cent. of silicon, the change is not perceptible. If the silicon content exceed 16 per cent., compound Fe_3Si_2 separates from the austenite besides the carbide.

7. The A3 and A1 points rise, their magnitudes decrease as silicon increases; but the A2 point falls, so that the latter change takes place at a lower temperature than the A1 change, provided the silicon content exceeds a certain limit.

8. The graphite found in this system is not a primary product from the melt or the austenite, but a secondary product decom-

posed from the carbide set free, gases probably acting as a catalyser.

9. The readiness of the graphite formation in this system depends on the facts that (1) the silico-carbide primarily separated is very unstable; (2) silicon diminishes the solubility of carbon in the melt or austenite, and (3) silicon raises eutectic and eutectoid temperatures. In other words, the carbide, which is easily decomposable, begins to set free at higher temperatures than in the case of iron-carbon alloys.

10. As the cooling rate decreases, and the silicon content increases, the degree of graphitisation is greater. With a quick cooling, the solid solution containing silicide and carbide, whose magnetic transformation is 550° to 450° , is seen. This constituent readily decomposes into graphite and silico-ferrite.

ANNUAL DINNER.

THE Annual Dinner of the Iron and Steel Institute was held on Thursday, May 10, at the Connaught Rooms, Great Queen Street, W.C., Mr. Francis Samuelson, President of the Institute, in the Chair. The attendance numbered some 350 persons, among whom were the following: The Right Hon. Lord Invernairn of Strathnairn (Past-President), The Right Hon. Lord Airedale of Gledhow (Vice-President), The Right Hon. Lord Gisborough, D.L., The Right Hon. J. Hodge, M.P., Signor F. M. Taliani, C.B.E. (First Secretary to the Italian Embassy), Sir William H. Ellis, G.B.E., D.Eng. (Vice-President), Sir Richard Redmayne, K.C.B. (Chairman of the Imperial Mineral Resources Bureau), Dr. Arthur Cooper (Past-President), Sir Frederick Mills, Bt. (Vice-President), Dr. W. H. Maw (President of the Institution of Civil Engineers), Sir William J. Larke, K.B.E. (Director of the National Federation of Iron and Steel Manufacturers), Sir John Dewrance, K.B.E. (President of the Institute of Mechanical Engineers), Sir John W. Beynon, Bt., C.B.E., Sir Rhys Williams, Bt., D.S.O., K.C., Mr. Leonard Sumner (President of the Institute of Metals), Sir J. R. Wright, and Colonel Sir W. Charles Wright, K.B.E., C.B.

The usual loyal toasts were proposed by the President and duly honoured.

Sir WILLIAM H. ELLIS, G.B.E., D.Eng., Vice-President, in proposing the toast of the Guests, said that it had been hoped that two members of H.M. Government—Sir Philip Lloyd-Greame and Sir William Joynson-Hicks—would have been present to reply to the toast. Unfortunately they had been unable to attend. The Department of Overseas Trade, over which both those gentlemen had at some time presided, was a great help to industry generally. At a time when the King and Queen were enjoying the hospitality of the Italian nation it was likewise a pleasure to toast Signor Taliani, the Secretary of the Italian Embassy, who was also present.

He offered a specially warm welcome to the Presidents of other Technical Institutions who had honoured the Institute by their presence that night. In that connection he thought he ought to make particular mention of that grand old man, the recipient that morning of the Bessemer Gold Medal, Dr. Maw, President of the Institution of Civil Engineers.

He was glad that Mr. John Hodge would reply on behalf of the Guests. He had naturally kept that *bonne bouche* to the end. For many years members of the Institute had had relations with trade unionism in various forms ; indeed, trade unionism was a necessity when one had to deal with large masses of men. Co-operation and organisation were essential, and he (Sir William) could say without fear of contradiction that John Hodge had throughout his life endeavoured to keep the peace and to hold the balance fairly between the men he represented and the employers, whom the members represented. Mr. Hodge had always aimed at something higher than the mere temporary settlement of industrial controversy, and he had been aided in his task of securing industrial peace by the fact that the members of his Union had been necessary to the industry of the country, and that fact, coupled with his able administration, had piloted his section of the industry through troublous times in safety. There had undoubtedly been less unrest and fewer strikes in connection with the Society that Mr. Hodge represented than in the case of any other trade union in the country. All credit was due, therefore, to the man who had been its representative for so many years.

The Rt. Hon. JOHN HODGE, M.P., said he found himself in somewhat of a dilemma, as he had not known he was to have the honour of replying to that toast. He had been informed that morning that a certain leading railway company was going to Belgium for their tires and various other requirements. That was perhaps an old story. Why, however, did the Institute put up with it ? The Trade was informed it would get the order if the price was made not more than 25 per cent. over pre-war price. He (Mr. Hodge) believed that, in some instances, the railways charged 300 per cent. over pre-war freights ; at any rate, they did not carry anything at 25 per cent. over pre-war rates. The steel trade ought to organise itself politically in the

way that labour, and indeed other industries, had done. He was very pleased indeed to be with them that night, a solitary member of his class amongst so many of them. Were it not that he looked upon every manager in the steel trade as a personal friend, he would be sinking under the table with fear. Sir Frederick Mills expressed some doubt as to that. Sir Frederick Mills and he were old opponents. After Sir Frederick went to Ebbw Vale, on one occasion when he (Mr. Hodge) went down there he was swanking terrifically about an alleged victory he had won and, of course, he (Mr. Hodge) was very humble about it. A few months afterwards, however, the tables were turned, but Sir Frederick was always a good sportsman. He said, after being knocked out of the ring in the first round, "I deserved it." What could he (Mr. Hodge) say after that? As a Yorkshireman would say—"Nowt."

He was glad to think that it was the steel trade which first evolved the idea of Whitleyism, and he hoped that as time went on the spirit which animated employers and workmen in the steel trade, and for which it stood, would dominate industry generally.

The Rt. Hon. Lord GAINFORD, in proposing "The Iron and Steel Industries," said that he wished, in the first place, to deal with the existing situation as to fuel, upon which the iron and steel trades so largely relied, and subsequently on the position of the iron and steel trades, and on what steps those industries could together take to meet world competition so as to secure that prosperity, which was the subject of his toast.

Before the beginning of the present year, the coal, iron, and steel industries had made a tremendous effort to recover their trade, which had fallen into abeyance during the cessation of operations at the collieries in the year 1921. Those industries had made an effort, and with the help of the workmen who engaged in them were getting their trade back and into a sound condition. It could only be done by very great sacrifice, and had indeed been done in that way. During the year 1922, instead of the coal trade receiving anything like the pre-war profit of 1s. 6d. per ton, which prevailed in 1913 over the whole country, they had to be satisfied with an average profit of 3½d.

a ton. That was not a living wage for an industry such as the coal trade. He could not help feeling that amongst the adverse influences at work was the occupation of the Ruhr by the French.

He recognised that the coal trade had secured a fillip from that occupation, but he did not regard that as a satisfactory feature in connection with world trade, which was suffering, owing to France and Germany trying to outstay one another on each side of the Rhine. The coal trade had improved, and was having great difficulty to meet the demands made by the iron and steel trades for fuel, owing to the great demand at a higher price which was obtainable from abroad. Those who, like himself, were interested in blast-furnaces and in iron and steel should realise that it was most important for England as a nation to cultivate the export of coal at a high price, so that they might obtain from abroad not only foodstuffs necessary for the life of the population, but also those raw materials which were absolutely essential if the manufacturing industries of this country were to be carried on. By increasing effort colliery owners had secured an export of coal which was to-day even greater than what it was before the war. Taking the price in the north-eastern district, coke could be sold for shipment abroad at 60s. a ton, whereas the average price, delivered to blast-furnaces, was something like 44s. a ton. In other words, with a view to maintaining home industries, and with a view to maintaining permanent customers, colliery owners had felt it their duty to sacrifice over 20s. a ton in the price of coke in order that the iron and steel trades might be maintained and the blast-furnaces kept in operation. Figures were often more eloquent than words. The output of coal in 1913 sent abroad per month was 7,000,000 tons. In 1921 it was only 2,187,000; in 1922 it was 5,661,000 tons, of which half went to Belgium, Holland, France, and Germany. In March of the current year 7,470,000 tons were exported, of which those four countries he had mentioned, their immediate neighbours, took 4,843,000 tons. To-day the capacity of the collieries of Great Britain had reached its limit with the restricted hours of work of seven a day as compared with the eight that prevailed up to the year 1918. More men, however, were being employed, and he was glad to say that the men, after a considerable sacrifice, were now receiving some increases in wages which he believed would

continue, and that in the next few months the men employed by the collieries would be contented by reason of those further increases. In 1913 there were 338 blast-furnaces in work in Great Britain. In June of 1921 they had to be damped down, owing to that disastrous cessation of work in the collieries. It took a year before 115 could be lighted up; that was in June 1922. In December 139 were in blast, and the present figure was 214, so that a real effort had been made to recover the pre-war position in the production of pig iron. Whilst, in 1913, 855,000 tons a month were being produced in Great Britain, the present figure was 665,000 tons.

In regard to steel, as against 639,000 tons which were produced monthly before the war, the present figure was 802,000 tons, so that the steel trade had more than recovered its position as compared with 1913, although, of course, it was not anything like up to the standard of September 1920, which was the high water-mark of the steel trade. The greatest credit was due to those engaged in the steel trade—owners, officials, and workmen—for having made a united effort to recover the steel trade of our country. On the one hand, great sacrifices had had to be made; on the other, the industry had been overburdened by taxation and rates and railway charges.

Looking at the steel trade from another point of view, and comparing the position to-day with that which prevailed in 1913, the price of steel in 1913 was £7 10s. per ton, while to-day it varied from £9 10s. to £9 15s. The railway tariff in 1913 was 19s. 8d. a ton, while to-day it was 32s. 6d. Those were figures taken from the north-eastern corner of the country. Whilst much more had to be paid in railway rates and fuel, a very much smaller increased price was being received for the steel. The industry had been going through a continuous struggle during the past few years, and most of those engaged in it had had to face heavy losses. It had been a question of whether they should run their blast-furnaces and steelworks at a greater or less loss than would be involved if they remained idle. He was glad to say, however, that there had been an improvement in the production of steel in the last two or three months, and that in the month of March 368,000 tons of steel had been exported as compared with 340,000 tons the previous December.

Very keen competition would have to be faced in the future from other countries. The United States of America produced during the war steel which enabled her to send out in one month 6,500,000 tons. In 1920 she was sending 4,700,000 tons, and in December last over 3,000,000 tons—3,087,000—half a million tons a month more than she was able to export in 1913. The United States made three times as much steel as was made in this country at the present time, but this country had maintained its position as being able to export more steel than America. He hoped that position might continue.

Whilst the iron and steel trades had been unable to employ more individuals than before the war, in June 1921 63 per cent. of the workers in the industry were unemployed; in December of 1921 the percentage was 36; in June 1922 it was 29 per cent.; last December it was 22 per cent., and at present it was only 15 per cent. of those formerly engaged. There had therefore been a steady improvement, not only in the amount of steel manufactured and in the amount which it had been possible to export, but in the employment which the industry was able to give to the working classes.

What would be the remedy that would enable the industry to meet the competition which was inevitable as soon as a settlement was made in the unfortunate position on the Continent? He did not believe in Government interference. He thought the industry had had enough of Government control. Lord Joicey gave a very good illustration of Government control in the House of Lords. He said: "I had been trying to secure for several months a new colliery rope because the old one was worn out. I could not get leave for a very long time; I had to send in estimates of all sorts and all kinds of details before, at last, I was able to get a reply, and that was only the result of three telegrams sent to the Control Department. Then a letter came. It said: 'If you want a colliery rope, we think you had better purchase half the length which you suggest, as that will be sufficient to go on with.'" That afternoon he (Lord Gainford) had been fighting with the Board of Trade in order to prevent legislation being rushed through the House of Lords which would have the effect of compelling those who shipped bulk goods abroad to accept the weights of the foreign buyer rather than of the

exporter. The export trade of Great Britain had been built up on the integrity which exporters had displayed in connection, amongst other things, with the weighing of materials. Weights were taken at the collieries; the railway companies were paid on those weights, and in most cases they were accepted by the foreigner and money was paid on their basis. It was setting back the clock if the Government passed legislation to force the exporters to accept the foreign importer's weights. The way to improve industry was by continued effort, whole-heartedly given on the part of everyone; the securing of a great reduction in railway charges, and by amalgamating and co-operating one with another so as to eliminate as far as possible unnecessary competition. The economy which could be secured by central administration in buying and selling in bulk, and so securing the best prices in the markets of the world, must appeal to everyone. He was conscious of the difficulties in the way, but, on the other hand, the bankers had set a good example of how to amalgamate and protect their interests.

There was another direction in which something could be done to help the prosperity of the iron and steel trades. It was necessary to concentrate the various establishments, and put their heads together so as to produce the most economical size of plant. Yet another direction, perhaps a still more important one, was to spend money in trying to improve processes and in research work. The Mine Owners' Association had recently authorised a large sum of money to be spent on research work in connection with fuel, and he believed other organisations ought to do the same. The interests of coke-ovens, blast-furnaces, and rolling-mills were identical.

Existing conditions notwithstanding he believed there was a silver lining in the clouds which were overhanging the iron and steel trade, but it was only through British grit, British determination, and British enterprise that trade could be made to flourish in the way they all desired.

Sir FREDERICK MILLS, Bart., Vice-President, who responded, said that the toast which Lord Gainford had proposed was one which did not usually appear on the Toast List, and in looking back to see how previous speakers had dealt with it, he had

had to go back nine years, to May 1914. On that occasion the cosmopolitan nature of the gathering was referred to. Thirteen or fourteen different countries, including Germany, were represented. Within three months those countries were at war.

The iron and steel industry had passed through two or three very bad years. Many people were delighted when the French went into the Ruhr, and personally he did not blame them. He hoped they would occupy the Ruhr for ever, though he did not expect anyone else to agree with him. Sooner or later, however, some sort of settlement, either a French settlement or a German settlement, of the Ruhr question would take place, but until it did there was going to be a good time for Great Britain. When a settlement was reached, however, what was going to be done with it? He had listened with the greatest possible respect to Lord Gainford, and he agreed with what he had said as to the methods which must be adopted to improve the home industry, but, in his judgment, that alone would not be sufficient. The cost of steel was largely made up by the cost of the labour engaged in producing it; labour charges represented 90 to 95 per cent. of the cost of the product, and wages were based on the cost of living. The wage of a German steel-worker to-day was 6d. He would like to ask his friend, the Rt. Hon. John Hodge, the question: "How are we going to pay men in this country 10s. a day, or £1 a day, or £2 a day, and compete successfully with a country where wages are 6d. a day?" Sooner or later there would be a settlement in Germany, and that country, owing to its depreciated currency, would be in an excellent position to compete with Great Britain in the markets of the world. That would right itself in time, but what was going to happen in the interim? Not only that, but Russia was capable of becoming a great steel-making country. The same arguments would apply in the case of Russia. He thought that a good deal of sympathy was being wasted on Germany and Russia, and other countries like them. Was not the British Empire big enough for trading within its own borders? It contained every kind of raw material; it manufactured every known article of commerce. Why could not the people of that great Empire take in one another's washing for a time and see how it worked? A very good example of what could be done in that direction was furnished by the United States. Seeking some information on that subject the other

day he applied to his friend, Mr. Dye, the Commercial Attaché at the American Embassy, and, with that thoroughness which distinguished the American nation, the information he required was immediately forthcoming. "How much," he asked, "does it cost to transport steel between certain given points in the United States?" He had received that information and had compared it with figures relating to the British Empire. He found that steel from Great Britain could be sent to Australia or Calcutta for less money than it took to convey steel from Pittsburg to New York or Baltimore. If such trade could be carried on by the United States of America, which had a ring-fence round it, why could it not be done in the British Empire? There were one-and-a-quarter million men unemployed in Great Britain, while the Dominions were short of labour. Why could not some of our labour go to the Dominions? Why could not they trade with us? The remedy for the conditions which were bound to prevail once a settlement was arrived at on the Continent could only be found by some measure of development within the Empire. It was big enough for its constituent countries to trade profitably amongst themselves.

As Lord Gainford had said, the industry had, at the present time, approached some degree of prosperity. He believed that prosperity would continue so long as the present conditions prevailed on the Continent. When, however, the time came for a settlement, he felt convinced that something more than technical education, something more than combinations of industry would be required to meet the competition which would then arise; what was wanted was a market, and that market, in his judgment, was clearly indicated.

The Rt. Hon. Lord GISEBOROUGH said he had the pleasant duty to perform of proposing the toast of "The Iron and Steel Institute." He had listened that evening to some most interesting and able speeches, and had heard a good many reasons given why the iron and steel trade, which was one of the principal trades of this country, was not in so satisfactory a position as might be wished. With some of those he agreed; with others he did not. His friend, Lord Gainford, seemed to think that the occupation of the Ruhr was wrong. Personally he (Lord Gisborough) agreed with Sir Frederick Mills. The only trouble

was, he thought, that if Great Britain had stood behind the French in their occupation of the Ruhr, Germany would have given in at once ; it was only because they counted on her intervening that they were hanging back from a settlement.

There were three obstacles, he thought, to the development of the iron and steel trade. One had been hinted at already, the introduction of foreign manufactured steel, which had been employed where British material should have been used. There were, however, two others. He could remember a time when the iron and steel trade of Great Britain was greater than that of any five other countries. Just before the war it did not hold the premier or even the second position, but was a bad third, America and Germany being ahead of it. Why had they beaten us ? It was because they had built up their industry by a tariff. The same was true in the case of Belgium. The rapid increase in production in the United States and Germany dated from the time of the Bismarckian and McKinley tariffs. Between 1870 and the present time Great Britain had increased her production sixteen-fold, while Germany, with her tariff, had increased her production sixty-fold, and America, with her tariff, had increased it two-hundred-fold.

The third obstacle to improvement in the industry was the delay which took place in handling and transporting goods. That, incidentally, led to higher freights. There was a scheme before the country which had never had fair play, but which, if adopted, would not only considerably accelerate the transport of goods, but would reduce the cost of transport to a very considerable extent. He referred to the Gattie Clearing House Scheme. He thought it should be adopted in all the great cities of the land. Many leading engineers had concurred that, under that scheme, it would be possible to expedite the delivery of goods and greatly to reduce the cost of freight. To take one example, in London alone there were over seventy-four goods stations occupying more than 3000 acres of land. In 1918, when prices were considerably higher than they were at the present time, chartered accountants had estimated the cost of a Gattie Central Clearing House for the whole London area at £26,000,000. That was a big sum of money. However, it had to be remembered that 1,460,000 trucks were in use at the present time on the railways, while under the Gattie scheme 100,000 trucks would

be more than sufficient, and would do the work better and more quickly than the 1,460,000 at present in use. That would mean 1,360,000 trucks to be discarded, with a corresponding saving in capital outlay. The average earning period of a truck was six minutes a day, due to the extravagant system at present employed. In the London area thirty acres would suffice for goods stations under the Gattie scheme. That meant that there were 3000 acres of London land that could be sold, having a value of at least £50,000,000. When compared with the required expenditure of £26,000,000 it would be seen that that represented a fairly high profit. That saving, moreover, would be effected in the London area alone, and in that area there would also be a computed saving in the cost of running of £6,000,000 a year. The scheme provided a cure for the industry of the country, and for agriculture, for agricultural products could be by it put more quickly into the market. It would reduce freight charges, which weighed so heavily on the big industries of the country. The committee which was charged with the examination of the scheme had however turned it down. Only one railway in England took it seriously, the North Eastern. That railway appointed a committee, which reported favourably on the scheme. He hoped a fresh committee would be appointed to inquire into it, or that a test would be made in some big city by establishing a central clearing house.

It was his pleasant duty to propose the toast of the Iron and Steel Institute, and to couple with it the name of one who was not only an old friend but also a relative, and who was a grand example of what an Englishman ought to be, industrious, hard-working, and a leader of industry, who also found time to be one of the greatest living philanthropists, whose sympathies and benefactions were at all times at the disposal of the sick or distressed. He asked them to honour, with him, the toast of the Iron and Steel Institute and of its President, Mr. Francis Samuelson.

The PRESIDENT, in reply, said he would not follow his friend, Lord Gisborough, into the details of the Gattie transport scheme, because he had not studied them, himself, very closely. He had been convinced by Lord Gisborough's eloquence, however, that it was something which, if it were properly taken up, would solve many of the problems with which industry in general was

confronted. He thanked Lord Gisborough for the kind things which he had said, and the members for the extremely kind reception they had given him.

The number of members of the Iron and Steel Institute at the end of the past year was 2237. He would like to see it double. It was very cosmopolitan in character; it was an international Institute, comprising members from some fourteen different nations. Foremost amongst the foreign countries was the United States, where there were 87 members, representing eighteen different States in the Union, the largest number being from the State of Pennsylvania. He hoped that the following autumn there would be a large access of Italian members. Their Italian friends had most kindly and generously invited the Institute to visit their country, and were making most excellent arrangements; he was sure they would give the members a most excellent time. He was very sorry that Signor Preziosi, of the Italian Embassy, had been unable to be present, but, on the other hand, the Institute had the privilege of having with them that evening Signor Taliani, the First Secretary of the Embassy.

Dealing with the home country, Yorkshire provided about 500 members, and the London district between 250 and 300. He was very sorry that Dr. Stead, one of the most distinguished Past-Presidents of the Institute, was not present that evening owing to ill-health. Another of the Institute's most distinguished members who was unable to be present, but from a happier cause, was Sir Hugh Bell, who was abroad. There was present that evening Dr. Maw, whom he knew, through personal acquaintance, to be a thorough sportsman. He was glad to see that Dr. Maw's recent indisposition had not prevented him from attending both at the Dinner and at the early session that morning.

Reference had been made to the coal situation. The real essential of the industry was that the country should possess its own ample supply of fuel. Whilst it was most desirable that as much iron and steel as possible should be made out of native ores, they were not as vitally necessary to the industry as was native coal. Ores were obtainable from many parts of the world and could be economically smelted in British furnaces. He hoped that Great Britain would take the precaution of securing her fair share of those ores and not allow the important ore deposits of the world to be monopolised by other nations.

SECTION II.

*NOTES ON THE
PROGRESS OF THE HOME AND FOREIGN
IRON AND STEEL INDUSTRIES.*

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In the preparation of these Notes the Editor has been assisted by L. P. SIDNEY,
Assistant Secretary, and others.

IRON ORES

AND OTHER METALLIFEROUS ORES USED IN THE IRON AND STEEL INDUSTRY.

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I.—GEOGRAPHICAL DISTRIBUTION OF ORES.

(Arranged in alphabetical order under Countries.)

Canada.—G. A. Young, *Iron-Bearing Rocks of Belcher Islands, Hudson Bay* (Canada, Geological Survey, Summary Report, 1921, Part E, 61 pp.). The iron formation is of the banded siliceous type common in Ontario, 300 to 400 feet in thickness. The exposures of iron formation and of iron ore are along the eastern edge of Flaherty Island, the principal island of the group, on a long peninsula that skirts its eastern side, and on two long islands that lie parallel to this side at a distance of six to twelve miles. The parallel outcrops of iron formation are parts of one bed folded and then eroded so as to present these various exposures.

A. H. A. Robinson, *Titanium* (Canada, Department of Mines, Mines Branch, Ottawa, 1922). A comprehensive report giving information on titanium and its compounds, the occurrences of titanium in Canada, and the world's sources, production, and uses of titanium. All the known occurrences of titanium in Canada that are of any possible economic interest are in the provinces of Quebec and Ontario. Ilmenite in commercial quantity, and carrying 20 to 30 per cent. titanium, is found in two localities in Quebec, at St. Urbain in Charlevoix county and Ivry in Terrebonne county. There is enough rutile mixed with the ilmenite in parts of one of the St. Urbain occurrences to make it of possible importance for the rutile alone. The rest of the Canadian titanium occurrences that are large enough to be of possible importance are all titaniferous magnetites, seldom carrying more than 15 per cent. of titanium. The report also contains a bibliography of literature on titanium.

China.—C. Y. Wang, *The Mineral Resources of China* (Tientsin Press, Ltd., pp. 54). The mineral resources of China are reviewed, and a brief summary is given of the geological history of that country. There are two different classes of iron ore deposits, those of igneous origin, usually found along the contact zone, and bedded deposits, some of which are undoubtedly sedimentary. Tables are given of the principal deposits showing their locality, typical analyses of the ore, and estimated reserves of each deposit. Analyses of the different kinds of coal from the different provinces are also tabulated. The following deposits are also dealt with: Tin, antimony, tungsten, manganese, gold, copper, lead, silver, zinc, mercury, arsenic, molybdenum, pyrite, nickel, cobalt, bismuth, platinum, and the non-metallic deposits.

Cuba.—P. M. Tyler, *Cuba's Duty Free Manganese Ore Supply* (Iron Age, January 25, 1923, vol. 111, pp. 275–277). Brief particulars are given of the manganese ore deposits in Cuba. Most of the mines are situated along the south coast, being found in the provinces of Oriente, Santa Clara, Matanzas, and Pinar del Rio. The only extensive deposits, however, are in Oriente. The deposits, which are estimated to contain 700,000 tons, are of great importance to the United States, but the mining costs are high and operations limited.

Germany.—Krusch, *The Occurrence and Origin of White Iron Ore* (Stahl und Eisen, November 16, 1922, vol. 42, pp. 1705–1708). In the peat bogs of Western Germany small pockets of so-called white iron ore occur which differs from bog iron ore, in that it is almost a pure carbonate iron ore. The origin of these iron ore pockets is discussed, and in view of the purity of the mineral it is thought it might be profitably mined.

H. Pohl, *The Manganiferous Iron Ore Occurrences at Waldalgesheim* (Zeitschrift für praktische Geologie, October–November, 1922, vol. 30, pp. 133–143). Several small deposits of manganiferous iron ore exist in the Hunsrück range on the left Rhine bank, and these are fully described and sections of the workings are shown. Two of the mines yield an ore containing 18 to 20 per cent. of manganese, 24 to 27 per cent. of iron, and 10 to 14 per cent. of silica. The third mine of the group has been worked at intervals from time immemorial, but is at present inactive; the lump ore from this mine runs as high as 60 to 65 per cent. MnO_2 . The total output of ore from the three mines up to the end of 1920 was 2,413,000 tons. The origin of the deposits is discussed.

India.—H. C. Jones, *The Iron Ores of Singhbhum and Orissa* (Records of the Geological Survey of India, 1922, vol. 54, pp. 203–214). The most important iron ore area in India is situated some 150 to 200

miles to the west of Calcutta in the Province of Bihar and Orissa. The deposits are remarkable for the enormous quantities of extremely rich ore they contain, and will undoubtedly prove to be among the largest and richest of the world. The Bengal Iron Company, the Tata Iron and Steel Company, the Indian Iron and Steel Company, Messrs. Bird & Company, and Messrs. Villiers have all been granted or have applied for mining leases in the area. The first-named company works deposits at Pansira Hill and Buda Boru Hill, the ore of which averages 64 per cent. of iron with phosphorus 0·05, and sulphur 0·002 per cent. The Tata Company's area contains ore of about the same iron content with phosphorus up to 0·08 and sulphur from 0·015 to 0·030 per cent. The minimum quantities estimated up to the present for ore of not less than 60 per cent. of iron amount to 2,832,000,000 tons.

Russia.—Roidot, *The Iron Ores of Krivoï-Rog* (Revue de l'Industrie Minérale, Mémoires, December 1, 1922, pp. 644-654; February 1, 1923, pp. 75-88). A description of the Krivoï-Rog ore-field written during the Russian revolution, to serve as a guide to future reconstructional work in the region. In 1913, out of a total output, for all Russia, of 9,376,000 tons of iron ore, no fewer than 7,000,000 tons were mined in this region. The ore contains from 60 to 65 per cent. of iron, 5·0 to 9·0 per cent. of silica, and 0·02 to 0·08 per cent. of phosphorus. The town of Krivoï-Rog is 180 kilometres north of the Black Sea and not far from the harbours of Nikolaef and Kherson. It is 400 kilometres from the Donetz coal basin. A list of the most important mines and details of their pre-war output are given, and the geological structure of the ore-field is described and illustrated. The ore in sight has been estimated at 73,370,000 tons and the reserves have been estimated at 207,800,000 tons. As, however, the depth of the deposits is not known these estimates are largely guess-work. Roughly each metre in depth of the deposits corresponds with 1,108,000 tons, hence the 1913 output corresponds roughly with an overall removal of some 6 metres depth of the deposits, and the estimated ore in sight, which represents a 30-years reserve at normal outputs, would extend to an average depth of 300 metres, allowing for an average uniform depth of cover. During the first two years of the war the Krivoï-Rog deposits were worked normally, but in 1917 the dislocation of affairs began to make itself felt, and by March the disorganisation had already become considerable. Before November many of the mines had become flooded, and work had been very generally suspended, but the situation became hopeless in December 1919. The present position is that nothing is being done at the mines, and that stocks, amounting roughly to 1,000,000 tons, remain available but unused, although the surface buildings and machinery have been maintained in a fairly satisfactory condition. The first step to restore working would be to pump the water away, and there is little doubt

that a number of large mines could be easily drained and work resumed at once if circumstances permitted.

A description is given of the mineralogical and petrological characters of the deposits, and the pre-war methods of working are likewise described and illustrated.

Switzerland.—O. Wilhelm, *The Manganiferous Iron Ore Deposits in the Lower Val Ferrera, Grisons* (Zeitschrift für praktische Geologie, December 1922, vol. 30, pp. 149–164). The deposits were opened in 1917 and were actively worked till the end of 1918. Analyses of the ore from the workings at Starlera show manganese ranging from 18 to 40 per cent., with corresponding percentages of iron from 30 to 8. At one working a true manganese ore containing 55·81 per cent. manganese is found. The origin and geological conditions of the deposits are discussed.

United States.—*Iron Ores, Fuels, and Fluxes of Washington* (Division of Geology, Department of Conservation and Development, Washington, Bulletin No. 27, pp. 160). A complete report on the iron ores of Washington. Most of the ores in the State are magnetites and limonites.

W. S. Bayley, *General Features of the Brown Hematite Ores of Western North Carolina* (United States Geological Survey, 1922, Bulletin 735–F.). The deposits which are of commercial importance are located in Cherokee and Madison counties. The ores are mixtures of hard goethite, limonite, and soft sandy limonite. They average 45 to 50 per cent. of iron, 0·25 to 1·25 manganese, 0·3 to 0·7 phosphorus, and 8 to 18 per cent. of silica. The sulphur content is rarely more than 0·1 per cent. The ores of the Piedmont Plateau in Gaston county contain 50 to 64 per cent. of iron and not more than 0·08 per cent. of phosphorus.

W. S. Bayley, *General Features of the Magnetite Ores of Western North Carolina and Eastern Tennessee* (United States Geological Survey, 1922, Bulletin 735–G.). These ores consist of brown hæmatite, magnetite, and titaniferous magnetite mixed in various proportions. Several mines in the district are described and typical analyses are given of the ore.

D. P. Rohlfing, *Iron Ore Deposits of Southern Utah* (Engineering and Mining Journal Press, April 21, 1923, vol. 115, pp. 716–719). A description is given of the iron ore deposits that are to be exploited by the newly organised Columbia Steel Corporation. The deposits are situated in the Iron Springs District. The ore is a mixture of magnetite and hæmatite. At the surface hæmatite composes about one-third of the mixture, which also contains a little iron carbonate. The average composition of the ore is as follows: Iron, 58·00; manganese, 0·20; silica, 6·50; phosphorus, 0·20; lime, 4·00; alumina, 1·00; sulphur, 0·05; water, 3·00; and a trace of copper.

A. C. Gill, *Chromite of Kenai Peninsula, Alaska* (United States Geological Survey, 1922, Bulletin 742). The ores are mixtures of

chromite and olivine and seem to have been formed by early crystallisation from a highly magnesian magma. Fourteen deposits at Port Chatham and twenty-three at Red Mountain are described. The only chromite mining in Alaska was the production of about 2000 tons in 1917-1918 at Claim Point.

G. W. Stose and F. C. Schrader, *Manganese Deposits of East Tennessee* (United States Geological Survey, 1923, Bulletin No. 737). The report comprises outlines of the topography and geology of the area, descriptions of the several types of ore deposits, and of their relations to the topography and geology, and brief descriptions of the mines. A tabular summary of the known deposits in the area is appended.

Mineral Resources of the World.—H. K. Scott, *The Principal Iron Ore Deposits of the World* (Proceedings of the Cleveland Institution of Engineers, Session 1922-23, No. 3, pp. 69-117). The author discusses the world's distribution of iron ore, and deals briefly with the composition of iron ores, their geological occurrence, and their impurities. Particulars are given of the following deposits: Lake Superior, France, Great Britain, Austria, Russia, Spain, Sweden, Newfoundland, North Africa, Cuba, India, Australia, South Africa, Chili, and Brazil.

Molybdenum (Imperial Mineral Resources Bureau, Mineral Industry of the British Empire and Foreign Countries, London, 1923). The report shows the distribution of molybdenite, and deals briefly with the uses of molybdenum, molybdenum alloys and steels, and the concentration of molybdenum ores. A bibliography of the literature dealing with the occurrence, mining, and metallurgy of molybdenum is appended.

R. H. Rastall, *Molybdenum Ores* (Imperial Institute, Monographs on Mineral Resources, London, 1922). A general account is given of the occurrences and commercial utilisation of molybdenum ore. A bibliography of the literature dealing with molybdenum is appended.

Nickel (Imperial Mineral Resources Bureau, Mineral Industry of the British Empire and Foreign Countries, London, 1922). The distribution of nickel in the chief producing countries is shown, together with statistics of production, imports, and exports. The report contains also a bibliography of the literature dealing with occurrence, distribution, mining, and metallurgy of nickel.

Meteorites.—G. P. Merril, *A Newly Found Iron Meteorite from Somerset County, Pennsylvania* (American Journal of Science, February 1923, vol. 5, pp. 175-176). A description of a piece of meteoric iron weighing about 40 pounds. It is thought to be a fragment of a meteorite found thirty years ago on Mount Joy, ninety miles away. An analysis showed that it contained 93.256 per cent. iron, 6.420 nickel, 0.325 cobalt, and 0.037 phosphorus, while sulphur, manganese, and copper were absent altogether.

G. P. Merrill, *A Recently Found Meteoric Iron from Glasgow, Barren County, Kentucky* (American Journal of Science, January 1923, vol. 5, pp. 63-64). Two pieces were found in a field. They were very badly oxidised and weighed about 25 and 20 pounds respectively. The iron is of the ordinary octahedral type. Analysis showed it to contain 70.632 per cent. iron, 7.270 nickel, and 19.22 nickel iron oxides. Chlorine was present to an amount of 0.363 per cent.

II.—MINING OF ORES.

Search for Iron Ore.—H. Louis, *Electrical Ore Finding* (Electrician, November 24, 1922, vol. 89, pp. 608-610). The author describes a method worked out by H. Nathorst and H. Lundberg in Sweden. The method depends on the modifications produced in the distribution of a current sheet through the earth, due to the great difference in electrical conductivity between most metalliferous ores and ordinary rock. The electrodes providing the earth current consist of galvanised wire ropes attached to rows of spikes driven into the ground. Two such electrodes are placed in long parallel lines about 200 metres apart, and a current from a 200-volt alternating-current hand or power driven generator is passed through the earth between them. A telephone method of exploration is used to discover the direction of the lines of flow of the current by plotting equipotential lines. Two spikes are driven into the ground some metres apart, and the telephone is connected between them. One of the spikes is then moved about till no sound is heard in the telephone, indicating that the two spikes are at equal potential. By taking a large number of observations a complete chart of the equipotential lines in the area can be obtained on which the position of conducting masses can be noted.

Methods of Mining Iron Ore.—S. R. Elliott, J. E. Jopling, R. J. Chennour, and E. L. Derby, *Mining Methods of Marquette District, Michigan* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). An illustrated description is given of the methods of mining iron ore in the Marquette District, together with a brief account of the geology of the district. There are no rich ores close enough to the surface to permit of open pit mining, and only the lean ores are now mined in open pits.

E. Duvivier, *The Development of Iron Ore Cutting in the Eastern Iron Ore Mines of France* (Revue de l'Industrie Minérale, Mémoires, January 15, 1923, pp. 39-64). The introduction of the eight-hours day in iron ore mines in France has accentuated the necessity of resorting to mechanical appliances for keeping up the output, the more so as hand-labour is becoming scarce, and is not as efficient as it was. A

short resumé is given of the history of iron ore cutting both by electrically and by pneumatically driven cutters, and tables are given showing the increased yield which can be obtained by these means, and the relative cost of machine, as compared with hand got ore.

Use of Liquid Oxygen as an Explosive in Iron Mines (Supplement to the *Revue de l'Industrie Minérale*, December 15, 1922, 84 pp.). The document consists of a full report of the Mining Association of Alsace-Lorraine on the development of the use of liquid oxygen as an explosive and results obtained therewith in the iron mines of that region.

M. H. Kuryla and G. H. Clevenger, *Liquid-Oxygen Explosives at Pachuca* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). The authors describe the preparation and use of liquid oxygen explosives at mines at Pachuca, Mexico. This is the first use of this type of explosive in America, although it has been adopted extensively in Lorraine and elsewhere in Europe.

III.—PREPARATION OF ORES.

Ore Roasting.—P. Oberhoffer and A. Weyel, *Tests on Siegerland Ore-roasting Kilns* (*Stahl und Eisen*, November 9, 1922, vol. 42, pp. 1673–1677). The kilns for roasting the spathic iron ores of the Siegerland are of an old-fashioned type, with open tops and natural draft. The kilns are of two forms of construction: either double cone, or cylindrical. The cylindrical is the more efficient of the two. The authors describe tests made with the object of discovering how the efficiency of the roasting process might be improved and some suggestions as to alterations of construction are made.

Magnetic Concentration and Briquetting of Ores.—H. M. Roche, *The New Magnetic Concentrating Mill at the Richards Iron Mine, New Jersey* (*Engineering and Mining Journal Press*, May 26, 1923, vol. 115, pp. 923–932). A brief historical sketch is given of iron mining in New Jersey during the last two hundred years. Present day changes in the methods of mining and milling are noted and detailed constructional features are given of the new Richards mill, including the general arrangement of the machinery, bins, coarse and fine crushing, and coarse magnetic concentration.

H. A. Brassert, *Raw Materials and their Preparation for the Blast-Furnace* (*Stahl und Eisen*, January 4, 11, 18, 1923, vol. 43, pp. 1–9, 44–49, 69–73). The article deals generally with American practice in the preparation of ore by magnetic concentration, sintering, and briquetting, working with fine ore, the use of acid slags, the management of coke-ovens, the quality of the coke and coke requirements.

Chemical Methods of Purifying Ores.—A. J. Moxham, *Chemical Methods of Iron Ore Purification* (Iron Age, January 4, 1923, vol. 111, pp. 31–32). The author has carried out an investigation extended over many years of the purification of iron ore. In the chemical method outlined all the ingredients of the ore are separated in pure form. The method consists of three stages: (1) Leaching with sulphuric acid with recovery of the acid; (2) calcination with carbonate of soda, with recovery of the carbonate; and (3) reduction of the oxide and subsequent melting.

REFRACTORY MATERIALS.

Bauxite.—R. B. Ladoo, *Bauxite: Occurrence, Mining, and Uses* (Engineering and Mining Journal Press, November 4, 1922, vol. 114, pp. 805–809). The United States is the principal source of bauxite. The types of deposits, methods of mining, and its uses in the manufacture of aluminium and refractories are dealt with.

F. Kerner, *Bauxites of the East Adriatic Coastlands* (Berg- und Hüttenmännisches Jahrbuch, Leoben, 1921–22, vols. 69 and 70, pp. 73–78).—The geological conditions of the bauxite deposits extending along the coast-lands of Dalmatia are fully described. The alumina percentage varies from 48·78 to 54·36, increasing slightly as the ore goes to depth. The ferric oxide varies from 17·76 to 22·56 per cent. and diminishes in depth, the sum of the two sesquioxides remaining about the same. The reserves are calculated to amount to about five million tons.

Graphite.—B. R. Rao, *Notes on the Occurrence of Graphite and other Economic Minerals near Marinhalli, Mysore District* (Mysore Geological Department, 1920, vol. 19, Part 2, pp. 117–128).

Magnesite.—G. W. Bain, *Magnesite Deposits of Grenville, Quebec* (Paper read before the American Institute of Mining and Metallurgical Engineers, August 1923).

Preparation, Properties, and Tests of Refractories.—H. S. Houldsworth and J. W. Cobb, *The Behaviour of Fireclays and Bauxites on Heating* (Transactions of the Ceramic Society, Session 1922–23, vol. 22, pp. 111–137). The methods adopted in the investigation have consisted essentially in taking the time temperature curve with a thermocouple embedded in the specimen and comparing it with the curve given by a second couple placed in some standard reference substance heated alongside of it. If at some temperature the former heating curves lag behind the latter, a change involving an absorption of heat is taking place in the specimen, but if at some point the rate of heating of the specimen is greater than that of the standard substance an exothermic reaction is occurring in the test-piece. The authors have prepared a large number of tables and curves, but they do not at the present stage attempt a complete explanation of the results obtained.

H. S. Houldsworth and J. W. Cobb, *Behaviour of Refractories on*

Heating (Paper read before the Ceramic Society, May 2, 1923: Iron and Coal Trades Review, May 4, 1923, vol. 106, p. 635).—An account is given of further experiments made to determine how far, if at all, the permanent shrinkages shown by clays on heating were due merely to decreases in porosity as distinct from volume changes in the clay material itself.

P. B. Robinson and W. J. Rees, *The Grading of Silica Bricks* (Paper read before the Ceramic Society, October 1922). The authors give grade analyses of green bricks and correlate them with the properties of the corresponding burned bricks. In general about 40 per cent. of the material was found to remain on a 30-mesh sieve, and about 40 per cent. passed through a 100-mesh sieve. Grading curves indicated that it was impossible, with ordinary pan-mill crushing, to get sufficient fine material to give a brick of appreciably less porosity than those at present made, as increased time of grinding only led to the production (in the various ganisters examined) of about 100-mesh size, and it was shown that for the production of a dense brick fine ground material from a ball-mill should be added.

A. H. Middleton, *Silica Bricks for Coke-Ovens* (Transactions of the Ceramic Society, Session 1922–23, vol. 22, pp. 169–198). A distinction is drawn between silica bricks made from quartzite or ganister rock containing about 97 per cent. SiO_2 , and quartz bricks containing from 77 to 85 per cent. of SiO_2 . The advantages of using silica brick in place of quartzite for the construction of coke-oven walls may be summarised as follows: Greater output and greater thermal efficiency; greater durability under ordinary conditions; resistance to corrosion where salty coal is used; and the possibility of varying the heat treatment where different classes of coal have to be employed. Tables are given showing the sizes, output, and carbonising period of several typical American installations, and details of coke and by-product yields from American silica brick ovens. Ovens of silica brick construction may be regularly worked without risk to the walls, at a temperature of from 1300° to 1400°C ., which is from 200° to 250°C . higher than is desirable with quartzite brick.

C. E. Moore, *Burning of Stourbridge Fireclay* (Transactions of the Ceramic Society, Session 1922–23, vol. 22, pp. 138–158).

C. N. Fenner, *The Reversible Expansion of Silica* (Paper read before the Ceramic Society, October 1922).

Sir W. H. Bragg and J. W. Mellor, *X-Radiogram of Kaolinite and the Thermal Decomposition of Clay* (Paper read before the Ceramic Society, October 1922).

A. L. Curtis, *An Examination of Refractories by the Oxygen Blow-Pipe* (Transactions of the Ceramic Society, Session 1922–23, vol. 22, pp. 199–204).

W. Smith, *A New Refractory Material* (Journal of the West of Scotland Iron and Steel Institute, Session 1922–1923, vol. 30, Part 1,

pp. 8-13). In former processes involving the use of clay and carbon the practice has been to mix these two substances together by mechanical means, in nearly all cases using carbon in the form of plumbago or powdered coke. The new process described involves the saturation of clay substance by volatilised carbon gases. To effect carbonisation an ordinary muffle kiln is used, and the coal and clay are so placed that on heating the volatiles given off will be absorbed by the clay until complete saturation occurs. Dissociation of the gases takes place within the clay substance, residual carbon being retained. A carbonised brick conducts with twice the efficiency of the standard firebrick.

A. G. Wikoff, *Fireclay Refractories* (Chemical and Metallurgical Engineering, November 15, 1922, vol. 27, pp. 969-971). The manufacturing methods for the production of fireclay refractories at the plant of the Laclede-Christy Clay Products Co., St. Louis, are outlined.

A Review of Twenty-five Years in Ceramics (Journal of the American Ceramic Society, January 1923, vol. 6, 343 pp.). The first number of the new volume of this journal is devoted to a review of the progress in the art of ceramics and refractories in the last twenty-five years. The following is a list of the papers dealing with refractories, their manufacture and applications :

R. M. Howe, *Fire-Clay Refractories* (pp. 275-277).

J. S. McDowell, *Chrome Refractories* (pp. 277-278). Chrome bricks have always been made very much in the same way as magnesite bricks. A binding material such as clay or lime was formerly used, but this is no longer done. The bricks are moulded in a power-press, semi-dry, dried in tunnel dryers and burned in rectangular down-draft kilns at an extremely high temperature.

H. G. Schurecht, *Technical Developments in Dolomite Refractories* (pp. 278-280). The chief research on dolomite refractories has been confined to determining the best methods for rendering dolomite dead-burned. The most common method is to mix an impurity with the ground material and to calcine the mixture at a high temperature. Fluxes high in alumina produce the most stable product. Numerous methods for the separation of magnesia from dolomite have been developed, and by most of the treatments a product containing 75 to 95 per cent. magnesium can be obtained. Recently sulphate solutions have been used for tempering dolomite brick, by means of which the free lime is converted into the insoluble sulphate, thus allowing the brick to be tempered, moulded, dried, and burned without danger of slaking. After firing the bricks may again be dipped in a sulphate solution and stored indefinitely without danger of slaking.

J. S. McDowell, *Magnesite Refractories* (pp. 280-285). Some notes on the technology of magnesite refractories are followed by an historical review of the use of magnesite in the metallurgical industries.

E. N. McGee, *Technical Development in the Field of Silica Refractories*

during the past Twenty-five Years (pp. 285–290). Deals with the uses of silica brick and its manufacture.

J. L. Crawford, *High Alumina Refractories* (pp. 290–291). A short account of the development and use of bauxite, diaspore, and aluminous fire-clay refractories.

M. F. Beecher, *Developments in the Manufacture of Refractories of Fused Alumina* (pp. 292–294).

M. Sheppard, *Zirconia Refractories* (pp. 294–296). The paper gives an outline of the physical properties of zirconium ore. Mention is made of zirconia laboratory ware and the method of its manufacture, and a note describes the manufacture and physical properties of zirconia brick.

R. M. Howe, *Testing of Refractories* (pp. 296–298). Deals with the development of the methods of testing refractories in the last twenty-five years.

E. N. McGee, *Comparison of the Hot and Cold Modulus of Rupture for Silica Brick* (Journal of the American Ceramic Society, December 1922, vol. 5, pp. 888–900). An investigation was carried out with the purpose of obtaining relative values for the transverse breaking of silica brick at temperatures usual in coke-oven practice, and it was also attempted to correlate the hot modulus of rupture test with the cold modulus of rupture test or cold crushing test, either of which is cheaper than the first. The method of testing is described. The conclusions show that the modulus of rupture of a silica brick at 1350° C. is approximately one-third the strength at atmospheric temperature. Too rapid or eccentric heating to red heat may cause such a weakening of the bond that the brick will break under very low pressure. The transverse strength decreases as the temperature increases. The hot test appears to give results in most respects comparable to the cold test, and for routine testing the cold test might well be used, since it can be made in much shorter time.

R. M. Howe, S. M. Phelps, and R. F. Ferguson, *The Action of Slag upon Silica, Magnesite, Chrome, Diaspore, and Fire-clay Refractories* (Journal of the American Ceramic Society, April 1923, vol. 6, pp. 589–595). The resistance of these refractories to the action of five slags was studied by a new method. The brick and slag were reduced to a powder, mixed in several proportions, and the fusion points of the mixtures were determined. Magnesite and chrome brick showed a particularly high resistance to the action of basic open-hearth slag, and brick made from diaspore was but slightly affected by the action of such slag. Silica brick showed a high resistance to the action of acid open-hearth and heating-furnace slags, both of which are composed almost entirely of silica and iron oxide. They showed a low resistance to the action of basic open-hearth and blast-furnace slags, which are high in lime. The behaviour of fire-clay brick differed considerably, as it does in service. In some cases, but not in others, high alumina appeared to be an advantage. Certain coal ashes are

found to attack bricks high in alumina more readily than those which are high in silica.

H. S. Houldsworth and J. W. Cobb, *The Reversible Thermal Expansion of Refractory Materials* (Journal of the American Ceramic Society, May 1923, vol. 6, pp. 643-662). The reversible thermal expansion from 15° to 1000° C. was measured for kaolin, siliceous, and aluminous fire-clays, quartzite, alumina, magnesia, and carborundum, after preliminary burnings at cones 06, 9, 14, and 20, and for English commercial silica bricks before and after use in a coke-oven and in the roof of a steel furnace. Siliceous fire-clays, after calcination at 980° or 1280°, display irregularities in their expansion, the nature of which is explained. No such irregularities were shown by magnesia brick, carborundum, or alumina bonded with 10 per cent. of ball clay. Welsh quartzite with lime bond, either unfired or after burning at 980° C., has a large expansion to 550° C., and a still larger one from 550° to 600°, due to the inversion of α to β quartz, while from 600° to 1000° a slight contraction takes place. Commercial silica brick consists chiefly of cristobalite and unconverted quartz, and shows a large expansion up to 300°, followed by a considerably smaller but regular one up to 550°. The rate of expansion then increases considerably up to 600°, beyond which it is small. The reversible thermal expansion from 15° to 1000° of the commercial silica bricks examined was 1.1 to 1.3 per cent., or about double that of fire-clay brick.

J. S. McDowell and H. S. Robertson, *Chrome Refractories* (Journal of the American Ceramic Society, December 1922, vol. 5, pp. 865-887). The report summarises available information on chromite and chrome refractories, their manufacture, properties, and uses. A bibliography on chromite occurrences and uses of chromium in the metallurgical industries is appended.

S. Sandlund, *The Addition of Chromium Oxide to Silica Bricks* (Jernkontorets Annaler, 1923, vol. 78, No. 2, pp. 45-52). The influence of chromium oxide as an addition to the silica bricks forming the lining of an open-hearth furnace has been investigated. The experiments show that the life of the bricks is prolonged thereby, but they have not been carried far enough to give definite conclusions.

J. G. Thompson, *A Preliminary Study of Zirkite Ore* (Journal of Physical Chemistry, December 1922, vol. 26, pp. 812-832). Zirkite is an impure zirconium dioxide containing silica, iron, and titanium among other impurities. To make it suitable as a refractory a mixture of the ore with coke is heated in an arc furnace, the quantity of carbon being sufficient to enable it to combine with the silica alone. By this means 90 to 95 per cent. of the silicon is removed. If the amount of carbon is in excess, the removal of silicon is less complete, owing to the formation of stable double carbides of zirconium and silicon. When the silicon is removed the iron can be eliminated by treatment with chlorine. Zirconium carbide is extremely refractory, but easily oxidised at high temperatures.

E. Rengade and E. Desvignes, *The Testing of Hardness of Refractory Materials at High Temperatures* (Chaleur et Industrie, 1922, vol. 3, p. 965). A method somewhat similar to the Brinell test is described for testing the hardness of refractory materials at high temperatures, a cone of 90° being used instead of a ball. A cylindrical test-piece, 50 to 60 millimetres in diameter, is placed in an electric furnace, pressure being applied by means of a lever through a graphite rod, to the end of which the cone is attached. The depth of the impression is taken as the measure of hardness. In tests on fire-clay bricks the alumina content appeared to have no effect on hardness, but the presence of 1 per cent. of alkali, or over, very adversely affects the hardness at high temperature.

W. J. Rees, *The Durability of Refractories* (Journal of the Royal Society of Arts, March 30, 1923, vol. 71, pp. 338-353). The composition, physical properties, and testing of refractory materials are discussed.

J. McMeekan, *Notes on Fire-Bricks, Fire-Clays, and other Refractory Materials* (Transactions of Institution of Engineers, Australia, 1921, vol. 1, pp. 380-387). The paper deals generally with the character, composition, and uses of fire-clay, silica, and magnesite, with some account of the prospects of developing the refractory industry of Australia.

H. Droust, *Refractory Materials* (Technique Moderne, 1923, vol. 15, Nos. 1 to 6, pp. 1-6, 37-43, 71-75, 104-111, 144-148, 170-176). The article contains a general account of practice in the selection and examination of refractory materials, the requirements to be met, methods of manufacture, apparatus used in the preparation of refractories, and the equipment of factories for their production.

M. Jakob, *Structure and Heat-Conductivity of Refractory Bricks* (Zeitschrift des Vereines Deutscher Ingenieure, February 10, 1923, vol. 76, pp. 126-127). Some experiments were made to account for discrepancies in the heat-conductivity values of different magnesite bricks. It was found that these were due to differences in the structure of the bricks.

K. Endell, *The Present Position of the Refractory Industry in North America* (Stahl und Eisen, March 15, 1923, vol. 43, pp. 361-370). The author reviews the information concerning the recent advances in the manufacture and standardisation of refractories in the United States collected by him during a visit to that country in 1922. Practice in the winning of raw material and the manufacture and testing of silica bricks is described, and the advantages derived from the research work by the American Ceramic Society and the progress in standardisation is especially emphasised.

A. F. Greaves-Walker, *Manufacture of Refractories in America* (Paper read before the Ceramic Society: Iron and Coal Trades Review, May 4, 1923, vol. 106, p. 631). The methods adopted in the United States for the manufacture of refractory products are outlined.

C. E. Nesbitt and M. L. Bell, *The Disintegration of Fire-Brick Linings in Iron Blast-Furnaces* (Paper read before American Iron and Steel Institute, May 25, 1923, 22 pp.). An investigation was made to determine the extent, position, and character of disintegrated bricks in blast-furnace linings after service, and to discover measures to reduce or prevent disintegration. If a brick contains free ferric oxide, carbon will be deposited when carbon monoxide passes over the bricks between certain temperature ranges. Experiments showed that with gas containing 10 to 25 per cent. carbon monoxide the action on the bricks was very slow, but with a gas containing 90 per cent. carbon monoxide a brick could be shattered in from six to ten hours. To prevent disintegration, bricks must be free from uncombined iron oxide and should be made from clay naturally pure, or, if such clay is not available, the clay should be freed from objectionable iron compounds.

C. E. Bales, *The Manufacture and Properties of Refractories for Air Furnaces* (Transactions of the American Foundrymen's Association, 1922, vol. 30, pp. 360-389). The manufacture of moulded and dry-pressed bricks for malleable iron furnaces is described. The composition and sizes of brick for various parts of the furnace are given.

M. H. Mawhinney, *Industrial Furnace Brickwork* (Blast-Furnace and Steel Plant, February 1923, vol. 11, pp. 145-147). The bricks in common use for steel furnace construction are classified according to the material from which they are made, and the various standard shapes are illustrated, with some notes on methods of repairing furnaces.

A. E. Mitchell, *Studies on the Dolomite System: The Nature of Dolomite* (Transactions of the Chemical Society, May 1923, vol. 123, pp. 1055-1069).

Kilns.—Sir A. Duckham, *Some New Forms of Kilns* (Paper read before the Ceramic Society, October 1922). A description is given of some new types of kilns for the burning of fire-bricks.

FUEL.

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I.—CALORIFIC VALUE.

Calorimetry.—R. Mezger and M. Müller, *Determination of the Calorific Power of the Volatile Constituents of a Coal, as a Measure of its Suitability for the Manufacture of Gas* (Gas und Wasserfach, 1922, vol. 65, pp. 793–794). A method is described in which a sample of coal weighing 0·3 gramme is distilled in a suitable apparatus and the calorific power of the volatile is determined as a measure for judging the suitability of the coal for gas-making. The results obtained with these small samples of 0·3 gramme are in close agreement with those given when using samples of 3 grammes.

P. Wedgwood and H. J. Hodsmen, *Determination of the Volatile Matter in Fuels* (Journal of the Society of Chemical Industry, December 30, 1922, vol. 41, pp. 372–373-T.). The method used was substantially the same as that specified by the United States Bureau of Mines, but as the use of the method depends on having apparatus of a simple and inexpensive kind, a substitute for the platinum crucible had to be sought for. After examining a number of metals and alloys two were found which gave complete satisfaction—namely, Monel metal and mild steel treated with aluminium powder by heating in a muffle.

Heat Value of Coke and Coal.—J. Blizzard, J. Neil, and F. C. Houghten, *Value of Coke, Anthracite, and Bituminous Coal for Generating Steam in a Low Pressure Cast Iron Boiler* (United States Bureau of Mines, 1922, Technical Paper 303).

Pulverised Coal.—J. T. Dunn, *Powdered Coal as Fuel* (Paper read before the North-East Coast Institution of Engineers and Shipbuilders, April 1923). The author discusses the different systems of burning and transporting pulverised fuel, and gives comparative figures showing the cost of using pulverised and solid fuel in reheating furnaces.

J. S. Atkinson, *Some Recent Developments of Powdered Coal Firing* (Paper read before the Bradford Engineering Society, November 27, 1922: Iron and Coal Trades Review, December 22, 1922, vol. 105, pp. 924-927). The preparation and use of powdered fuel is dealt with at length.

The Lopulco System of Pulverised Fuel Firing (Iron and Coal Trades Review, May 25, 1923, vol. 106, p. 790). The application of the Lopulco system to boiler firing is dealt with.

M. Sohm, *The Firing of Boilers with Powdered Coal* (Supplement to the Revue de l'Industrie Minérale, September 15, 1922, 27 pp.). The working results are reported of a powdered-coal fired installation at the mines of Bruay in the Pas de Calais. The plant has been in operation since January 1922, and it is affirmed that the introduction of the system of firing boilers with powdered fuel marks a distinct advance in fuel economy.

F. Schulte, *New Developments in Coal-Dust Firing* (Glückauf, March 3, 10, 1923, vol. 59, pp. 205-208, 240-247). The construction, the use, and the economy of the disintegration type of machine for pulverising coal are dealt with. The apparatus illustrated and described is the Walther-Farner mill with beaters and a centrifugal fan running at a high speed on the same shaft and in the same casing, and one of the same type manufactured by the German Babcock Wilcox Works. The results of firing with coal-dust produced by these mills are discussed. Some difficulty has been experienced in finding bricks for the combustion chambers of boilers which will withstand the action of the dust and the high temperature. At present 1500 hours is about the longest the walls and arches will stand, but it is expected that this problem will soon be solved.

W. Behling, *The Brown-Coal Pulverising and Firing Installation of the Becker Steel Works Company* (Stahl und Eisen, March 22, 1923, vol. 43, pp. 393-398). In consequence of the hindrances in the way of obtaining brown-coal briquettes for the gas-producers of their works at Willich the Becker Steelworks have abandoned the use of brown-coal producer-gas, which had exclusively supplied all the power required in the works, and have installed a drying plant for the raw brown coal, a mill for pulverising the dry coal, and a blowing plant for firing the furnaces with the brown coal-dust. The dust contains 12 to 18 per cent. of moisture and 50 per cent. volatile matter, with a calorific value of 4500 to 4800 calories. The ash content varies from 5 to 9 per cent. Reheating furnaces can be fired without preheating the air for combustion, consequently no recuperators are necessary, and the construction of the furnace is much simplified. It is also quite easy to work either with the theoretical quantity of air or with excess of air or of fuel, which enables the use of a neutral, an oxidising, or reducing atmosphere in the furnace at will. The time required to heat up a cold furnace with a hearth 2×8 metres to 1650°C . is two to four hours.

H. Kreisinger and J. Blizard, *Powdered Coal as Fuel in Steam Plants* (Proceedings of the Engineers' Society of Western Pennsylvania, June 1922, vol. 38, pp. 169-200). It is now definitely established that a higher thermal efficiency can be obtained in steam plants by burning coal in powdered form than by burning it in any other form. The high efficiency is due to the fact that very nearly complete combustion with low excess of air can be obtained. With 20 per cent. excess of air combustion is complete within 1 per cent., the 1 per cent. including both the gaseous combustible as CO in the flue gases and the unburnt carbon in the ashes. The principal results of several tests, averaging about twenty-four hours, carried out on a three-pass Edge Moor boiler rated at 468 boiler horse-power, show that the boiler efficiency based on gross calorific value of coal was 80.8 to 82.2 per cent., and on net calorific value it was 83.9 to 85.3 per cent. To prevent erosion of the fire-brick lining of the furnace by the molten ash, an air space is provided between the lining proper, which is 9 inches thick, and the outside walls. About 65 per cent. of the air needed for combustion is passed through these air spaces and is heated to about 450° F. before admission to the combustion chamber. The bottom of the furnace is kept cool by means of a tubular water-screen connected up with the boiler tubes, and the liquid ash, dropping on to the screen, is granulated before falling into the ash pit.

M. W. Arrowood, *Furnace Maintenance with Pulverised Fuel* (Iron Age, December 21, 1922, vol. 110, pp. 1633-1636). The author deals with the combustion of pulverised fuel, and points out the difficulty of ensuring the proper mixing of the dust particles and air. A feeding apparatus is described in which the necessary mixing is done outside the furnace.

E. E. Griest, *Use of Pulverised Coal in Malleable Foundries* (Transactions of the American Foundrymen's Association, 1922, vol. 30, pp. 447-482).

A. de Grey, *Experiments on Coal-Dust and Combustion of Pulverised Coal* (Revue de Métallurgie, Mémoires, November 1922, vol. 19, pp. 645-655). The article describes results of experiments on the propagation of dust ignition in mines and means of combating this danger, and shows the application of the results to the problems of combustion of pulverised coal.

Fusibility of Coal Ash.—W. A. Selvig and A. C. Fieldner, *Fusibility of Ash from Coals of the United States* (U.S. Bureau of Mines, 1922, Bulletin No. 209. See also last volume of this Journal, 1922, No. II. p. 273). The report describes the method of testing the fusibility of coal ash adopted by the Bureau, and gives the softening temperatures and sulphur and ash analyses of a large number of coals from all parts of the United States.

II.—COAL.

Great Britain.—Summary of Progress of Geological Survey of Great Britain and the Museum of Practical Geology for 1921. This constitutes the second Annual Report of the Geological Survey Board and includes particulars relative to survey work done in various coal-fields in Great Britain.

Austria.—M. Dolch and G. Gerstendörfer, *An Investigation of the Fuel Value of Austrian Coals* (Berg- und Hüttenmännisches Jahrbuch, Leoben, 1921–22, vols. 69 and 70, No. 2, pp. 21–40). Analyses of all coals mined in Austria are tabulated and in most cases the calorific values are appended.

W. Petrascheck, *Geology of the Coalfields of the Austrian Succession States* (Berg- und Hüttenmännisches Jahrbuch, Leoben, 1921–22, vols. 69 and 70, No. 2, pp. 1–20; No. 3, pp. 1–30). The first part of the article deals with the geology and palæontology of the chief coal-fields of the former Austrian Empire, and in the latter part the character of the coals and their composition are described.

Borneo.—C. F. J. Galloway, *Notes on Coal in Sarawak, Borneo* (Proceedings of the South Wales Institute of Engineers, 1923, vol. 39, No. 1, pp. 31–38). In Sarawak a lignitic coal of superior quality has been worked on a small scale by the Government for the last forty years at Sadong. Coal of good quality is known to exist at Silantek, and the State of Sarawak has in this coalfield an asset of immense possibilities, the extent of which is not yet known.

China.—M. Brücher, *The Coalfields and Coal-Mining Industry of China* (Glückauf, October 14, 21, 28, November 11, 1922, vol. 58, pp. 1225–1229, 1253–1259, 1283–1287, 1349–1355). A full description is given of the chief coal occurrences in China and of the present state of the development of the coal-mining industry; an excellent map accompanies the article.

France.—Moulinier, *The Utilisation of Alpine Anthracite* (Memoir presented to the Liège Congress, June 1922: Revue de Métallurgie, Mémoires, October 1922, vol. 19, pp. 600–608). The anthracite fuel in the French Alps consists of a number of parallel veins running from north-east to south-west, from Briançon towards the Little St. Bernard, and across the valleys of the Arc and of the Isère. They extend some 150 kilometres in length and are on the average 7 to 8 kilometres in width, although, near St. Michel-de-Maurienne and Modane, they widen out to 16 kilometres. Several outcrops occur, which are worked by the local inhabitants for their own domestic needs, and there is

little doubt that considerable fuel is available throughout this region. The anthracite possesses very peculiar characters and weathers badly. It cannot, moreover, be obtained in large pieces and an undue proportion of "fines" exists. The volatile matter is very low. Hence the anthracite is exceedingly difficult to light, and even to keep burning. Sometimes as little as 3 to 5 per cent. of volatile matter is present, and the anthracite assumes the appearance of a graphite, while, on the other hand, the ash is very high, sometimes reaching 30 to 35 per cent. Its physical condition is such that it does not lend itself to ordinary methods of washing, and experiments on cleaning by flotation processes have not, on the whole, furnished very satisfactory results. It is suggested that many of the difficulties would disappear if this anthracite was pulverised and used in the pulverised state. It is probable that, in the future, this practice will increase in favour. In the meanwhile, very satisfactory results have been obtained in small experimental installations, where the Alpine anthracites have been pulverised, and as very considerable supplies exist, they may have an important influence on the future industrial development of the localities in which they occur.

Germany.—R. W. Clarke, *The Coalfield of Upper Silesia* (Iron and Coal Trades Review, April 6, 1923, vol. 106, pp. 495). The geographical features, exploitation, and development of the Upper Silesian coalfield are briefly described. It lies in the south-east of Upper Silesia. It is bounded on the north by a line running east from Peiskretscham, on the west by a line running south from Gleiwitz. To the south the coalfield extends in Czechoslovakia, where it is known as the Mährisch-Ostrau coalfield. It extends into Poland on the east, where it is known as the Dombrowa coalfield. The Upper Silesian portion has an area of about 760 square miles, and a conservative estimate of the reserves is 90,000 million tons.

Philippine Islands.—*Coal in the Philippines* (Iron and Coal Trades Review, January 12, 1923, vol. 106, p. 49). According to information furnished by the Division of Mines of the Bureau of Science, coal is found in twenty-four localities, fairly well distributed over all the Islands. The coal from the Gotas area, which was the first to be exploited, is semi-bituminous. The Butong area produces a semi-anthracite coal. The following are analyses of various local coals, all of which are non-coking:

	Gotas Coal. Per Cent.	Butong Coal. Per Cent.	Camp Wilmott Coal. Per Cent.
Fixed carbon	73·60	80·69	73·14
Ash	5·91	3·04	9·76
Volatile matter . . .	18·81	14·13	14·45
Moisture	1·68	2·14	2·65
Sulphur	0·70	0·96	0·88
B.Th.U.	14,767	14,942	14,942

South Africa.—*Mineral Resources of Northern Rhodesia* (Bulletin of the Imperial Institute, 1922, vol. 20, No. 3, pp. 337-344). Coal is found in four seams, aggregating about 19 feet in thickness, in the Luano Valley on the north-eastern boundary of the territory. The coal is bituminous in character, and includes some with a low proportion of fixed carbon. The probable reserves are about 22 million tons, with large possible reserves. A second coalfield is found at Lufira and Losito on the Zambesi River. The probable reserves are estimated at 38 million tons.

Spain.—H. M. Morgans, *The Villablino Coalfield, Spain* (Transactions of the Institution of Mining Engineers, 1923, vol. 64, pp. 129-136). The occurrence of coal and the method of mining are briefly described.

United States.—*Analyses of Kentucky Coals* (United States Bureau of Mines, 1922, Technical Paper 308). This report contains numerous chemical analyses of mine samples of Kentucky coals. It also includes a brief description of the geological structures of the coal basins in the State.

D. D. Condit, *Economic Geology of the Summerfield and Woodsfield Quadrangles, Ohio* (United States Geological Survey, 1923, Bulletin 720). This report consists of detailed information concerning the coal and other mineral resources, except oil and gas. The western half of the area extends into the Cambridge coalfield, and the eastern half includes the Pittsburgh coal-bed.

C. R. Fettke, *Cannel Coal and Carbonaceous Shale Deposits of Pennsylvania* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). The composition of the cannel coals and shales and of the oils derived from them are described, also the characteristics of the more important deposits.

E. O'Toole, *Pocahontas Coalfield and Operating Methods of the United States Coal and Coke Co.* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). The history of development in the Pocahontas coalfield and the occurrence of the coal-seams are outlined, and the mining methods employed by the United States Coal and Coke Co. at Gray, West Virginia, are described in detail.

A. C. Fieldner, W. A. Selvig, and J. W. Paul, *Analyses of Mine and Car Samples of Coal collected in the Fiscal Years 1916 to 1919* (United States Bureau of Mines, 1922, Bulletin 193). The results are given of analyses of hundreds of coals from twenty-five States of the United States and Alaska. The heating values of all coals tested are also given. Particulars of the sampling and analytical methods employed, and a bibliography of the coal resources of the world, are included.

Terminology of Coal Constituents.—M. C. Stopes and R. V. Wheeler, *Terminology in Coal Research* (Fuel, January 1923, vol. 2, pp. 5–9). The authors draw attention to the confusion caused by the wrong use of terms intended to be descriptive of the constituents of coal, and they repeat the definitions of terms first proposed and adopted by Dr. Marie Stopes in her previous paper (Royal Society, December 12, 1918). Fusain, durain, clarain, and vitrain are the four distinguishable ingredients of banded coal, and each contains α -, β -, and γ -compounds which may be isolated by treatment with pyridine and chloroform. Compounds isolated by treatment with other solvents should not have these names applied to them without giving proof of their identity. The term "humic substances" should be dropped, as it may lead to confusion with the substances called humic by geologists and humus by agriculturists.

Constitution of Coal.—A. Baranov and W. Francis, *Banded Bituminous Coal* (Fuel, 1922, vol. 1, pp. 219–222). A sample of coal from the Top Hard seam of East Kirkby Colliery was examined. The lower portion of the seam consists almost entirely of dull hard coal, durain. The upper portion consists of durain with several bands of clarain and the middle portion of several thick bands of vitrain. When small samples were exposed to the action of anhydrous hydrofluoric acid and concentrated nitric acid, then neutralised with potassium hydroxide, and an excess of water added, the whole of the vitrain passed into solution. The clarain yielded a similar solution, but with transparent solid fragments held in suspension. About half the durain passed into solution which was of a light yellow colour. On fusion the reagent had no action.

F. V. Tideswell and R. V. Wheeler, *Dopplerite: Studies in the Constitution of Coal* (Transactions of the Chemical Society, 1922, vol. 121, pp. 2345–2362). Dopplerite is the name by which the jelly-like deposits found in peat-beds are known. It is essentially a mixture of acid anhydrides, in which oxygen is present mainly as hydroxyl. When dried it shrinks to a hard black shining substance very similar in appearance to the black vitrain constituent of bituminous coals. The gaseous products of low-temperature distillation are also similar to those of vitrain.

W. N. Edwards, *The Microscopic Structure of Coal* (Paper read before the Royal Microscopical Society, April 25, 1923). The study of the microscopic structure of coal dates back to Henry Witham (1833), but little progress was made by this method until recent years, owing to the difficulty of preparing thin sections. A general review of the work that has been performed in this branch of science is presented.

S. R. Illingworth, *Some Economic Aspects of the Chemical Constitution of Coal* (Proceedings of the South Wales Institute of Engineers, 1922, vol. 38, No. 6, pp. 499–542).

G. S. Haslam and R. V. Wheeler, *Contact Photographs of Coal* (Fuel, 1922, vol. 1, pp. 42-47). The ability of coal to affect a photographic plate in the absence of light is described. This method affords an insight into the structure of the coal and makes it possible to take approximate measure of the proportions of vitrain and fusain.

G. E. Foxwell, *The Plastic State of Coal* (Paper read before the Coke-Oven Managers' Association, April 27, 1923: Iron and Coal Trades Review, May 11, 1923, vol. 106, pp. 706-707).

A. Grounds, *A Study of the Constitution of Anthracite* (Fuel, January-February, 1923, vol. 2, pp. 10-14.).

D. Florentin, *The Constitution of Coal* (Genie Civil, November 4, 11, 1922, vol. 81, pp. 408-412, 437-440). The author reviews in a serial article the results of researches of recent investigators of the constitution of coal.

S. R. Illingworth, *Action of Solvents on Coal* (Fuel, 1922, vol. 1, pp. 213-218). Extractions of coal were made with pyridine, boiling phenol, aniline, and other agents, and diagrams are given of the apparatus used. The components which are most difficult to dissolve are those of higher carbon : hydrogen ratio.

Occurrence and Preparation of Peat.—E. K. Soper and C. C. Osbon, *The Occurrence and Uses of Peat in the United States* (United States Geological Survey, 1922, Bulletin 728). The report deals at length with the origin of peat, its physical properties, chemical composition as shown by about 1000 analyses, uses, and the peat industry of the United States.

J. W. Hinckley, *The De-watering of Peat by Pressure* (Journal of the Society of Chemical Industry, December 30, 1922, vol. 41, pp. 365-368-T.). The difficulty of de-watering peat by mechanical means is well known. The author has devised a method, which he claims to be efficient and effective. It consists of warming the peat to the boiling point of water and slowly applying pressure up to half a ton per square inch. By this means the water content of Norfolk peat can be reduced by 50 per cent. and with Doncaster peat a reduction of 55 per cent. in the amount of water was possible. Ekenberg stated that a temperature of 150° C. was necessary to destroy the colloidal matter, but it is now shown that the entire destruction of the colloidal matter need not be carried out in order to remove the water successfully.

III.—COKE.

Properties and Tests of Coke.—Sir G. Beilby, *The Structure of Coke, its Origin and Development* (Journal of the Society of Chemical Industry, November 15, 1922, vol. 41, pp. 341-347-T). The paper discusses the changes observed in coal and similar substances during the process

of carbonisation and describes experiments carried out on the micro-structure of coke and charcoal. Use is made of the new knowledge concerning the internal constitution of solids for which Sir William Bragg is largely responsible. The structure of coke is very much determined by the size of the bubbles blown in the viscous mass during the semi-liquid stages of carbonisation, and even what have been commonly regarded as the solid vitreous cell walls of the pores have been shown to be permeated by minute bubbles. The bubble formation can be controlled by blending coal of different behaviour, and a strong hard coke with small and evenly distributed pores can be obtained by blending a coal which froths and swells inordinately with a non-caking coal.

Durnerin, *The Cokes of the Saar District and Upper Silesia* (Revue de l'Industrie Minérale, Mémoires, August 1, 15, 1922, pp. 415-434, 446-460; Genie Civil, September 30, 1922, vol. 81, pp. 299-300). The character of the coke obtained from the coals of the Saar Valley and Upper Silesia is described. The Saar coke is fingery, small and brittle, though hard. That of Upper Silesia is even less good, being extremely friable, and apt to crumble on being discharged from the oven.

T. Gray, *The Determination of the Caking Power of Coal* (Fuel, March 1923, vol. 2, pp. 42-45). For the determination of the caking power of a coal it is very desirable to have a convenient laboratory test, capable of standardisation and of giving trustworthy results. A modification of the Campredon method is described, which would appear to embody all the requisites of a standard method, if a satisfactory substitute for sand can be discovered.

A. Badarau and F. V. Tideswell, *The Caking Power Curves of Coal* (Fuel, April 1923, vol. 2, pp. 61-65). The variation in the compressive strength of coke as the proportion of coal and inert material in the mixture is varied has been studied. The ultimate and proximate analyses of the coals used were known, and it is shown that they tend to group themselves into two classes—the first having a high initial coking strength which rapidly falls on addition of inert material, and the second having a low initial coking strength which rises considerably on addition of inert material and then falls gradually.

S. P. Kinney and G. St. J. Perrot, *Shatter and Tumbler Tests for Metallurgical Coke* (Report to the U.S. Bureau of Mines: Journal of Industrial and Engineering Chemistry, October 1922, vol. 14, pp. 926-931). The shatter test for blast-furnace coke consists in dropping 50 lbs. of the coke from a height of 6 feet on to a steel plate and ascertaining the percentage remaining on a 2-inch screen. The sample should be composed of large pieces about half the width of the oven. The tumbler test, in which a sample is placed in a drum and rotated a given number of times, fails as a measure of the resistance of the coke to abrasion, since the proportion of coke remaining on a $\frac{1}{4}$ -inch screen is largely determined by the size of the pieces in the tumbler after a few turns—that is, by their resistance to impact. Different cokes, especially

when using small coke of 0.25 to 0.75 inch, give very similar results, and this test appears therefore to have very little value. The shatter test, however, affords a measure of the relative resistance of cokes to breakage in handling. Single determinations by this method show an average error of 1 to 3 per cent., depending on the character of the coke tested.

A. Schmolke, *A New Method for Determination of Strength of Coke* (Glückauf, January 6, 1923, vol. 59, pp. 3-6). Test-pieces of coke are prepared by reducing lumps to a suitable size with a hammer, and then grinding one side to a flat surface. The piece is then fixed in a holder and pressed by means of a loaded lever against the side of an emery wheel, running at 2340 revolutions per minute. The centre of the test-piece rests against the wheel at a distance of about $3\frac{1}{2}$ inches from its centre, and a pressure of 1 kilogramme is employed to hold it in position. The resistance to friction is measured by the weight of dust in grammes removed in one second. The method enables a good comparison of the hardness of different cokes to be made.

H. J. Rose, *Determination of the True Specific Gravity of Coke* (Journal of Industrial and Engineering Chemistry, November 1922, vol. 14, pp. 1047-1049). Some of the methods in use for the determination of the true specific gravity of coke vary in important respects. The author has made experiments to show the effect of the degree of pulverisation of the sample, the nature of the liquid used, the time of boiling, and the effect of partial vacuum. When 60-mesh coke samples were pulverised to pass a 200-mesh sieve, the true specific gravity was found to increase by as much as 12.7 per cent. The greatest increase was noted in cokes made below 800° C. When the effect caused by a change of liquids was examined, benzene was found to give the lowest results. The figures for the specific gravity using benzene were 8.1 per cent. lower than those obtained by using water. The true specific gravity is usually determined for the purpose of calculating the porosity, and the discrepancies due to the particular procedure followed as indicated above, when expressed in terms of porosity, amount to as much as 30 to 50 per cent. of the total variation in porosity which will be found in blast-furnace cokes.

W. A. Selvig and W. L. Parker, *The Determination of the Specific Gravity of Coke* (Chemical and Metallurgical Engineering, March 21, 1923, vol. 28, pp. 547-550). The experiments described were undertaken to develop a method for determining true and apparent specific gravities of metallurgical coke. True specific gravity may be satisfactorily determined by boiling the pulverised coke in water at atmospheric pressure for one hour in a convenient calibrated pycnometer. The experiments indicate that it is not necessary to boil the sample under reduced pressure, or to boil at atmospheric pressure for periods longer than one hour. Somewhat higher results were obtained for true specific gravity on coke samples pulverised to pass a 200-mesh sieve as compared with the same samples pulverised to pass a 60-mesh sieve.

It is not advisable to use other media besides water, as the results may not be comparable. In determining the apparent specific gravity of lump coke a correction should be applied for water absorbed. The method for determining apparent specific gravity, using a sample of 20 to 30 lbs. of large pieces of coke, and correcting for water absorbed, is recommended.

E. R. Sutcliffe and E. C. Evans, *The Reactivity of Coke as a Factor in the Fuel Economy of the Blast-Furnace*. (This Journal, p. 27.)

R. A. Sherman and J. Blizard, *Combustion of Blast-Furnace Cokes in Fuel Beds* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). An account is given of an experimental investigation undertaken to determine the relative combustibilities of different samples of blast-furnace coke when burned in a current of air in a small furnace.

F. Fischer, P. K. Breuer, and H. Broche, *Determination of and Causes of Ease of Combustibility of Coke* (Brennstoff-Chemie, 1923, vol. 4, pp. 33-39). A method is described for measuring the ease of combustibility of coke by determining the temperature at which the coke begins to reduce carbon dioxide to carbon monoxide.

K. Bunte and A. Kölmel, *Ignition Temperatures of Various Cokes* (Gas und Wasserfach, 1922, vol. 65, pp. 592-594). On testing various kinds of coke under constant conditions, constant and characteristic results were obtained. It was found that the ignition temperature depends on the size of the coke pieces, on the speed of the current of gas in which the coke is heated, and on the concentration of oxygen in the gas. An increase in any of the three factors lowers the temperature of ignition.

H. Koppers, *Foundry and Furnace Coke Compared* (Die Giesserei : Iron Age, March 22, 1923, vol. 111, pp. 825-827). Attention is drawn to the radically different requirement of coke for furnace and foundry use. The finishing temperatures in the coke-ovens have great influence on the quality. A specification is given and recommended by the author covering the two distinctive varieties of coke.

A. Young, *Coke Requirements of the Iron Trade* (Paper read before the British Foundrymen's Association : Foundry Trade Journal, November 23, 1922, vol. 26, pp. 420-422). The general requirements and properties of foundry coke, the methods for the testing of coke, cupola troubles in relation to coke, coke economy in relation to cupola practice, are discussed. The determination of phosphorus in coke is also described.

A. R. Powell, *Forms of Sulphur in Coke and their Relations to Blast-Furnace Reactions* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). Coke contains four characteristic sulphur constituents—namely, ferrous sulphide, adsorbed free sulphur, sulphates, and sulphur held in solid solution in the carbon. In the reduction zone of the blast furnace the only sulphur reaction of any importance is the reduction of the free sulphur

of the coke to ferrous sulphide. In the iron sponge zone, considerable sulphur is taken up by the iron from the coke. The ferrous sulphide of the coke gives up sulphur at this point. The presence of lime in intimate contact with the coke practically prevents the sulphur of the coke from reaching the iron. In the zone of the preliminary slag formation the adsorption of sulphur by the iron is practically prevented by the slag. In the final or combustion zone the sulphur is probably entirely adsorbed by the slag. In this region, the slag also removes from the iron the excess sulphur which was taken up by the iron in the spongy iron zone.

Coking Practice.—D. W. Wilson, *Thermal Operation of Modern Regenerator Coke-Ovens* (Industrial and Engineering Chemistry, March 1923, vol. 15, pp. 251–254). Thermal efficiency tests were made on a 60-oven battery of regenerator ovens producing blast-furnace coke, with the object of obtaining a comprehensive heat-balance of the ovens and to determine their thermal efficiency. The coal used was mixed so as to give about 27 to 28 per cent. volatile in the mixture, and the heat effect of coking this particular mixture was studied.

J. Becker, *By-Product Coking with Particular Reference to New Combination Oven* (Blast-Furnace and Steel Plant, November 1922, vol. 10, pp. 575–583). The author compares American and European methods of coking, giving reasons for the great advances made in American practice as compared with the practice followed in England and on the Continent. Modern American ovens will carbonise more than double the quantity of coal per day that can be coked in ovens as built in Germany and England. The main reason for the greater speed of coking in America is the general use of silica brick in the construction of the ovens, combined with better design and more systematic operation. The design of new coke-oven plants of the Koppers type is illustrated.

A. Coe, *By-Product Coke-Oven Operation* (Blast-Furnace and Steel Plant, December 1922, vol. 10, pp. 619–622). The uniformity of the coke depends upon pushing the ovens in correct series. Diagrams of pushing series are shown, and several other factors on which the uniform heating of the oven charges depend are discussed.

D. S. Chamberlain and E. W. McGovern, *By-Products Oven Heat-Balance* (Gas Age Record, February 17, 1923). The authors give a complete heat-balance for a battery of Koppers by-product coke-ovens.

J. Van Ackeren, *Heat Distribution in New Type Koppers Coke-Oven* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). The proper application of heat to coke-oven walls is discussed, and particulars are given of the design of the new Koppers oven which operates on the cross-over flue principle.

J. W. Spencer, *Difficulties met with in Re-starting a Battery of Coke-Ovens* (Paper read before the Coke-Oven Managers' Association :

Iron and Coal Trades Review, March 30, 1923, vol. 106, p. 457). The battery in question consisted of fifty waste heat ovens and ten vertical flue regenerative ovens, with the usual by-product plant. Charging was stopped on October 16, 1920, owing to the coal strike, and the ovens were sealed up and made air-tight. An examination was made of each individual oven each day, and after the first week it was deemed advisable to admit a little air to the hot coke and so increase the heats. The temperature of the flues averaged on shutting down 950°C ., and on November 4, when charging was resumed, the average temperature was 1020°C . Only a small amount of coke was lost due to admission of air, as normally the production was 4 tons 18 cwt. per oven, while the coke drawn after the stoppage was 4 tons 15 cwt. per oven.

Carette, *The Problem of Fuel Economy in Coke Manufacture: The Recuperation of the Heat of Glowing Coke for Steam Raising* (Revue de l'Industrie Minérale, Mémoires, October 1, 1922, pp. 523-526). An enormous amount of heat is wasted every time some 6 to 8 tons of glowing coke are drawn from the ovens, and little attempt has hitherto been made to render it commercially available. It averages 320,000 to 350,000 calories per ton of coke, equal to about 35 per cent. of the total heat required for the carbonisation of the coal used. The Sulzer process has been devised to solve the question, and a description is given of a Sulzer plant installed at the Zurich Gasworks in 1919. Here the coke is eventually dumped into a chamber where its heat can be utilised either for regenerating the gases or, indirectly, for steam raising.

A. Thau, *Mechanical Coke Quenching and Transport Appliances* (Stahl und Eisen, December 14, 21, 1922, vol. 42, pp. 1838-1843, 1868-1874). The article describes and illustrates some modern coke-quenching installations and conveyors for loading coke into trucks. Reference is made to the recent development, by Sulzer Brothers of Winterthur, of a method of cooling coke by passing neutral gases through the glowing mass after discharge from the ovens, partly with the object of utilising the sensible heat, but chiefly to improve the quality of the coke by dry cooling instead of wet cooling.

Kuckuk, *Dry Cooling of Coke by the Sulzer System* (Gas und Wasserfach, November 18, 1922, pp. 729-734).

Dry Coke Cooling Plant (Colliery Guardian, January 19, 1923, vol. 125, pp. 148-149). Illustrated particulars are given of the Sulzer method for the dry cooling of coke and the utilisation of the waste heat for steam raising. The coke is dumped into a receiver which is enclosed in a common shell with a set of steam boilers. The cooling chamber shell is built in concrete or iron and lined with firebrick. The coke is cooled in contact with a neutral gas which is circulated by a fan through the receiver and boiler. Coke is withdrawn at the bottom of the receiver at approximately the same rate as the charging. A cooling period of from three to four hours has proved to be ample for cooling the coke down to 200°C . It is claimed that for blast-furnace

work the use of dry-cooled coke will reduce by 1 to $2\frac{1}{2}$ per cent. the amount of fuel used and improve the working conditions in the furnace.

Dry Cooling of Coke (Iron and Coal Trades Review, January 5, 1923, vol. 106, p. 13). A lengthy abstract is given of the paper by P. Schläpfer which appeared in Stahl und Eisen, August 17, 1922, vol. 42, pp. 1269-1275.

By-Product Recovery.—R. A. Mott and H. J. Hodsman, *Factors Influencing the Yield of Ammonia in the Carbonisation of Coal* (Journal of Society of Chemical Industry, January 5, 1923, vol. 42, pp. 4-12-T.). The influence of water vapour and of the character of the contact materials, and the fire-bricks composing the oven walls, on the dissociation of ammonia is considered. The quantity and quality of the ash in coal and coke seem to have great influence on the yield of ammonia. The influence of atmospheres of coal gas, hydrogen, and nitrogen was examined.

Coke-Ovens.—M. W. Ditto, *Design and Operation of Roberts Coke-Oven* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). The Roberts oven is designed in three types: regenerative, recuperative, and the combination-regenerator oven, which can be heated by coke-oven gas or by blast-furnace and producer gas; or where it is necessary to pre-heat both the air and fuel gas. The fundamental principles of these designs are the same. The method of heat generation in the Roberts recuperative oven is described, and the operating results from the use of Illinois coal are given.

J. Becker, *New Combination By-Product Coke-Oven* (Paper read before the Eastern States Blast-Furnace and Coke-Oven Association: Iron Trade Review, October 19, 1922, vol. 71, pp. 1055-1062; Iron Age, November 16, 1922, vol. 110, pp. 1275-1279). In the new Koppers oven an entire side of the coke-oven chamber serves for up-flow combustion. The products of combustion pass through horizontal flues and over the top of the oven through cross-over flues and distribute downwards through the flues on that side of the oven. The new design permits of a great reduction in the cross-sectional area of the horizontal flues, which may be situated higher in the heating walls, so that the vertical flues can extend as far as necessary for the uniform heating of the top of the charge. This considerably shortens the time of coking. A battery of five of these ovens has been installed at the plant of the Chicago By-Product Coke Co.

Compound Regenerative By-product Coke-Ovens (Iron and Coal Trades Review, May 18, 1923, vol. 106, pp. 742-743). Illustrated particulars are given of the Otto compound regenerative coke-oven. This type of oven can be heated by coke-oven gas, producer-gas, or blast-furnace gas, or a mixture of such gases in any proportion.

By-Product Coke Capacity (Iron Age, January 4, 1923, vol. 111,

pp. 62-63). A table is given showing the by-product coke plant capacity in the United States on January 1, 1923. Details are given of the number, types and annual capacity of ovens owned by each individual firm. Pennsylvania still holds first place in the number of by-product ovens, the total for that State being 3520 out of a total of 11,931 for the whole of the United States.

C. R. Robson, *Variable Speed Hydraulic Transmission Gear Applied to a Coke-Oven Ram and Leveller* (Iron and Coal Trades Review, May 18, 1923, vol. 106, p. 749). A description is given of the first application of the variable speed hydraulic transmission gear to a coke ram and mechanical levelling machine.

Low Temperature Carbonisation.—H. A. Curtis and W. J. Chapman, *The Low Temperature Carbonisation of Coal* (Chemical and Metallurgical Engineering, January 3, 10, 17, 24, 1923, vol. 28, pp. 11-17, 60-64, 118-123, 171-178). The general features of the several low-temperature retorts built and tested at the plant of the International Coal Products Corporation at Irvington, New Jersey, and the evolution of the Clinchfield retort are described and illustrated. The results are also given of a number of tests carried out to ascertain the suitability of various types of coals for the Carbocoal process. The tests were carried out in small-scale apparatus.

A. Thau, *Low Temperature Carbonisation in the Inclined Rotary Furnace* (Glückauf, January 13, 20, 1923, vol. 59, pp. 29-35, 55-63). A description of a low temperature coking plant at Gelsenkirchen, with drawings showing the arrangement of the plant. The operation of the plant, the recovery of the products, the output and costs of working are dealt with in detail.

W. A. Bone, *Brown Coals and Lignites* (Journal of the Royal Society of Arts, January 26, February 2, 9, 1923, vol. 71, pp. 172-184, 189-199, 208-216). The origin and classification, characteristic properties, geographical distribution, and utilisation of brown-coals and lignites are outlined. The carbonisation of dried brown-coal containing about 30 per cent. of oxygen was carried out for the purpose of ascertaining and measuring the products given off at different temperatures. Oils were recovered above 375° C., the maximum yield being at about 750° C. Gaseous products were given off up to 850°, at which temperature the decomposition was complete. The residues are non-coherent, and can only be utilised as powdered fuel or by briquetting.

M. J. Bradley and S. W. Parr, *Decomposition Processes Applicable to Certain Products of Coal Carbonisation* (Chemical and Metallurgical Engineering, October 11, 1922, vol. 27, pp. 737-744). The authors describe experiments in which mixed xylenes were decomposed under varied conditions of temperature, pressure, and atmosphere.

J. S. Morgan, *The Lead Bath Process of Low Temperature Carbonisation* (Paper read before the Coke-Oven Managers' Association, March 25, 1923; Iron and Coal Trades Review, April 13, 1923, vol. 106, p. 530).

The author deals with low temperature carbonisation practice and refers to the use of the lead bath. The difficulty of heating charcoal was overcome by completely immersing it in a lead bath. The heating to the required temperature took fifteen seconds as against four hours. The lead bath has been successfully applied on a large scale to the distillation of coal-tar oil and many other things. The possibilities of the process are discussed.

IV.—LIQUID FUEL.

Australia.—L. J. Jones, *Notes on Petroleum and Natural Gas and the Possibilities of their Occurrence in New South Wales* (New South Wales Geological Survey, 1921, Mineral Resources, No. 31). The prospects of obtaining commercial supplies of oil in New South Wales are by no means bright. There are possibilities of oil being obtained from the Tertiary marine rocks in the vicinity of the lower Murray if suitable geological structures can be located. The Mesozoic rocks, may be disregarded as possible sources of oil. Of the Palæozoic rocks, the Coal Measures offer no prospects of obtaining supplies, but both the Upper Marine and Lower Marine beds may yet prove to contain oil. It would thus appear as if New South Wales will have to depend for its oil supplies, not upon deposits of crude petroleum, but upon the mining and distillation of oil shales, extensive deposits of which are known to occur within the State.

Canada.—W. J. Wright, *Geology of the Moncton Map Area* (Canada, Geological Survey, 1922, Memoir 129). An account is given of the oil-shale deposits of New Brunswick and Nova Scotia.

Germany.—G. von Emerick, *Oil Shale and its Utilisation* (Glückauf, February 3, 1923, vol. 59, p. 113–120). On account of the difficulty in procuring supplies of coal, attention is being directed in Germany to the oil-shale deposits of Württemberg, Brunswick, Bavaria, and Hanover. Experiments in direct firing have been made, but without much success on account of the high proportion of incombustible matter averaging 80 per cent. The only industry in which it can be used in this way with any prospect of advantage is the cement industry. The distillation of the shale is being promoted, and several distilleries are in operation. Reference to the utilisation of shale in other countries is made.

Italy.—M. Fenoglio, *Petroleum from Montechino-Velleia* (Giornale di Chimica Industriale ed Applicata, 1922, vol. 4, pp. 565–570). This region is at present the most productive in the province of Eurilio. An examination of a crude sample of petroleum shows that it has a

neutral reaction, and is free from hydrogen sulphide and unsaturated hydrocarbons. On fractional distillation it yields 54.6 per cent. of light oils (benzine), 34.7 per cent. of lighting oil, 7 per cent. of heavy oil, and 3.6 of a brown viscous residue.

Mesopotamia.—Milner, *Mesopotamia, a Review of its Geology and Petroleum Resources* (Mining Magazine, August 1922, pp. 88–90).

Mexico.—S. Huntley, *Oil Development on the Isthmus of Tehuantepec* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). An account is given of the petroleum industry of this district, together with drilling and production statistics.

Russia.—T. G. Madgwick, *Some Aspects of the Occurrence of Oil in Russia* (Journal of the Institution of Petroleum Technologists, February 1923, vol. 9, pp. 2–32).

Scotland.—E. M. Bailey, *The Shale Oil Industry of Scotland* (Journal of the Institution of Petroleum Technologists, October 1922, vol. 8, pp. 465–490). The methods of refining shale oil as carried out at a typical Scottish refinery are described at length.

United States.—D. White, *Oil Reserves of the United States* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1922). The estimated oil reserves of the United States amount to 9150 million barrels of 42 gallons.

J. Majorelle, *The Oil-fields of the Eastern United States* (Revue de l'Industrie Minérale, Mémoires, April 1, 1923, pp. 177–196). After a brief statistical account of the oil resources and output of the United States, and of the geology and petrology of the chief oil-fields, a description and maps are given of the Appalachian fields and of the Warren and Venago fields. The oil resources of each of the eastern States are then dealt with separately, the name of the oil, and of the gases, the output, and the average depths of the wells being given for each State.

D. Hager, *The Sunburst Oil and Gas-Field, Montana* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). An account is given of the geology, economic conditions, and working of this oil-field.

W. T. Thom, *Oil and Gas Prospects in and near the Crow Indian Reservation, Montana* (United States Geological Survey, 1922, Bulletin 736–B).

F. Reeves, *Geology of the Ranger Oil-Field, Texas* (United States Geological Survey, 1922, Bulletin 736–E). This report describes the geology of an area twelve miles square in Eastland County. The Ranger Oil-Field is one of the most productive fields discovered in the United States during the last five years.

A. J. Collier, *The Osage Oil-Field, Western County, Wyoming* (United States Geological Survey, 1922, Bulletin 736-D). In 1921 there were about 100 wells in this region with a combined daily yield of 500 barrels of oil. The location of many of the wells is described, and the relations of production to structure of the strata are indicated.

M. J. Gavin, *Oil Shale: An Historical, Technical, and Economic Study* (United States Bureau of Mines, 1922, Bulletin 210). A comprehensive report dealing with the present status of the petroleum industry of the United States, the world's deposits of oil shales, the nature and origin of oil shale, the chemistry of oil-shale distillation, the nature of the destructive distillation of oil shale, the history of the industry, the Scotch oil-shale industry and methods employed, the application of the Scotch industry to an American oil-shale industry, the history and present status of the oil-shale industry in the United States, and problems and future of the United States industry. The report also contains a selected bibliography of literature on the subject.

West Indies.—A. H. Redfield, *Petroleum Reserves of the West Indies* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1922). The West Indies (exclusive of Trinidad and Tobago) do not constitute a promising area of oil reserves. Most of the islands present unfavourable structures or composition.

Geology of Petroleum.—H. Höfer, *Origin of Petroleum* (Petroleum, 1922, vol. 18, pp. 1301-1302). Naphthene base oils are the most recent and paraffin base oils the oldest formations, the oils of naphthene-paraffin base being of intermediate age. The base of the oil is indicated by the geotectonic structure of the oil-field.

De Hautpick, *New Ideas in Oil Geology* (Mining Journal, November 18, 25, 1922, vol. 139, pp. 859-860, 880-881). The movement or flow of oil through rocks is shown to be the result of underground artesian waters. As the oil sands are fine and the artesian water movement is slow, slight structural and textural variations formed by gentle folding or faulting are insufficient to arrest this movement and to accumulate oil in commercial quantities, and the blind following of the anticlinal theory of oil accumulation has resulted in numerous failures.

J. L. Rich, *Moving Underground Water as a Primary Cause of the Migration and Accumulation of Oil and Gas* (Economic Geology, 1921, pp. 347-371). Many examples of oil occurrences are quoted as evidence against the theory that oil gas accumulates under the anticlinals of impervious strata owing to the rising of the lighter oil and gas while the heavier water sinks to the lower levels.

Mining Petroleum.—A. Millar, *The Galician-Canadian System of Pole Tool-Drilling* (Journal of the Institution of Petroleum Technologists, December 1922, vol. 8, pp. 617-665). The Canadian system

of drilling, which is exclusively used in the Galician oil-fields, is described and illustrated.

Testing Petroleum.—*Specifications for Petroleum Products and Methods of Testing* (United States Bureau of Mines, 1923, Technical Paper No. 323). Official United States Government specifications are given for gasolines, naphthas, burning oils, fuel oils, and lubricants, and methods of testing for various purposes a variety of petroleum products.

A. E. Dunstan, *The Standardisation of the Testing of Petroleum and its Products* (Journal of the Institution of Petroleum Technologists, December 1922, vol. 8, pp. 578–617).

Sulphur in Petroleum.—G. Egloff and J. C. Morrell, *Distribution of Sulphur in Petroleum Products* (Chemical and Metallurgical Engineering, April 9, 1923, vol. 28, pp. 633–635). The authors deal with the distribution of sulphur in the primary products resulting from cracking distillation of a hydrocarbon oil. The content of sulphur increases with the density of the liquid and solid products, but is higher in the gas than in any of the products. This is very closely analogous to the distribution of nitrogen in the destructive distillation of oil shale.

Production of Gasoline from Natural Gas.—*Cost of Producing Natural Gas Gasoline* (Chemical and Metallurgical Engineering, February 14, 1923, vol. 28, pp. 297–298). The scope of the industry in the United States is briefly outlined, and recovery costs for various types of plants are given.

V.—ARTIFICIAL GAS.

Gas-Producers.—T. R. Wollaston and A. L. Booth, *Recent Developments in Gas-Producers* (Journal of the Society of Chemical Industry, May 11, 1923, vol. 42, pp. 200–203–T). The construction of a new producer plant with ammonia recovery is illustrated and described. A feed-hopper feeds the fuel into a retort placed on top of the producer-chamber, and the retort also serves as the gas outlet pipe. The fuel descends very slowly through the retort being in contact with the producer-gas at a temperature averaging 500° C. for a period of about three quarters of an hour. The coked fuel is then distributed symmetrically into the chamber, which has no refractory lining, but is surrounded by an annular jacket which may be either a boiler for steam-raising or a water-heater. A hollow central cone is fixed in the producer, to the upper portion of which the blast-pipe is introduced,

and a controllable water-atomiser is fitted near the base of the vertical blast-pipe. The cone then acts as a flash boiler and superheater, and under ammonia recovery conditions it serves a double purpose in reducing the necessity for high-blast saturation while providing steam for such saturation as is required. In the retort ammonia up to 10 lbs. of sulphate is liberated, and it is expected that the total yield will be 80 lbs. of sulphate per ton of coal gasified. The low temperature and consequently smaller volume at which the gas will leave the retort and the low dust content are two points which favourably influence recovery operations.

J. Cohade, *The Gas-Producers at the Breuil Works of Messrs. Schneider & Co.* (Revue de l'Industrie Minérale, Mémoires, November 1, 1922, pp. 573-586). An illustrated description, with plans, lay-out, &c. There are two groups of producers installed, one with twenty-eight producers of the Hilger type for the open-hearth furnaces, and one with seven Morgan producers for the rolling-mill furnaces. The construction of the producers is fully described, as well as the practice, and tables are given showing the yield and the chemical composition of the gases, corresponding with the various fuel mixtures employed, analyses of which are likewise given.

G. Rivière, *Marconnet Ash-fusion Gas-Producer for Gasification of Coke Breeze* (Gas Journal, August 23, 1922, vol. 159, pp. 424-425). The producer consists of a rectangular chamber, provided with slag holes at the base. Openings are also provided for stirring the charge and for the admission of air and steam. During a test coke breeze containing from 14.8 to 34.3 per cent. of ash, and mixed with limestone and iron ore, was gasified at the rate of 405 kilogrammes per square metre of grate area per hour. The gas contained carbon dioxide 1.5, carbon monoxide 29, hydrogen 1.8 per cent.

H. Müller, *New Slagging Gas-Producer* (Chemiker Zeitung, 1922, vol. 46, pp. 828). Particulars are given of the two gas producers in operation at the Georgsmarienhütte. One is of 30 tons and the other of 45 tons per day capacity. About 18 per cent. of the charge is fresh blast-furnace slag which quickly becomes fluid and carries off the residue from the generator. No steam is required, consequently the gas is a dry gas consisting for the most part of nitrogen and carbon monoxide.

H. F. Miller, *Development of Gas-Producer Practice* (Blast-Furnace and Steel Plant, January 1923, vol. 11, pp. 48-51). In an article on modern developments in the design of open-hearth furnaces the author refers to the effect of the physical condition of the coal on the production and quality of producer-gas. The tonnage of a furnace using producer-gas from coal slack may be increased by 25 to 50 per cent. by using clean lump coal instead of slack. At the same time the coal consumption will decrease between 15 to 30 per cent. But the screening to get the lump coal produces a large amount of coal slack which is difficult to dispose of otherwise. The use of bituminous

coal is attended by an irregular supply and quality of gas, due to removal of clinker and ash and the cleaning the gas mains of soot. Attention is therefore directed to the slagging gas-producer, which was very much developed in Germany during the war. The bituminous coal was first coked to recover the valuable by-products. Then the coke, much of which was unsuitable for the blast-furnace, was charged into a producer of the form of a miniature blast-furnace. Air was blown through water-cooled tuyeres and the ash was melted and run off through a cinder notch, by which means clinkering is avoided. A small amount of open-hearth slag is added to each charge of coke to flux the ash, and this gives a free-running slag from which the iron content of the furnace slag can be recovered. A producer blown by air under pressure has a capacity about five times greater than that of a steam-blown gas-producer of equal dimensions using coal, and the gas has under 1 per cent. CO_2 and is clean and free from soot. The only objection is that the gas burns invisibly in the furnace and is therefore difficult to regulate, but there are means of overcoming this difficulty.

The Morgan Producer-Gas Machine in England, Scotland, and Wales, 1919-1922 (Iron and Coal Trades Review, October 27, 1922, vol. 105, pp. 608-609). A survey is given of working results obtained with the Morgan gas machine in Great Britain. This machine differs in every detail from the familiar Morgan gas-producer. The guiding principle of the machine is not to disturb the fire but to keep the surface of the fuel bed uniform all over, at the same time as the ash removal ensures an even level of the ash bed, and thus a fuel bed of even thickness. This is accomplished by a hinged horizontal water-cooled bar, called the leveller, reaching from the centre of the producer to the circumference. By means of counterweights it is kept pressed upon the fuel bed, automatically working up and down as the height of the coal may vary.

Gas-Producer Design (Iron Trade Review, November 16, 1922, vol. 71, pp. 1351-1354). An illustrated description is given of the Treat gas-producer. The distinctive features of this producer consist of a number of devices for automatically controlling the fuel supply, the continuous agitation of the fuel bed, the distribution and production of the blast, and the removal of the ashes.

A New Gas-Producer (Engineer, April 6, 1923, vol. 135, p. 364). The R. G. gas-producer with central cone through which a blast of heated air is blown is illustrated and described.

New Gas-Producer (Iron Age, March 22, 1923, vol. 111, pp. 817-818). This new design of producer is an improvement on the standard Hughes unit. It is self-contained and is automatic from coal feed to ash disposal. The constructional details are described.

V. Windett, *Gas-Producers and Producer-Gas* (Blast-Furnace and Steel Plant, January 1923, vol. 11, pp. 55-60). A general description of modern gas-producer practice is given.

Gas-Producer Practice.—F. Clements, *British Steelworks Gas-Producer Practice*. (This Journal, p. 97.)

R. T. Haslam and L. Harris, *Producer-Gas from Powdered Coal* (Industrial and Engineering Chemistry, April 1923, vol. 15, pp. 355–357). The attempts to use powdered coal for making producer-gas have never met with much success, and experiments have been made with a view to overcoming the difficulties, which were found to consist mainly in the production of a sufficiently high temperature in the reacting zone, and the maintenance of the necessary intimate mixing of the powdered coal and the reacting gas. Better results were obtained on heating the incoming air, and it seems desirable to preheat the air to 1000° C. The maximum amount of CO obtained in any good run was 10 per cent., although for short periods 12 to 13 per cent. was reached.

W. Dyrssen, *Gas-Producer Practice in Steel Works* (Paper read before the American Iron and Steel Institute, May 25, 1923, 67 pp.). The author discusses the heat and chemical balance in producers, the manufacture of gas from bituminous coal, the efficiency of producers, the temperature of the gas, the use of oxygen in gas-producers, the influence of the rate of gasification, the preheating of the blast, the use of waste gases in place of steam for cooling the fire zone, and finally gives a description of several types of modern mechanical producers.

A. Korevaar, *The Combustibility of Coal* (Stahl und Eisen, March 29, 1923, vol. 43, pp. 431–435). The zone of combustion in a gas-producer is defined, and it is shown that the factors which influence the volume of the zone of combustion are the activity of the coal, the porosity, and the size of grain of the coal. The volume of the zone is smaller the higher the activity and porosity and the smaller the grain size, and with constant velocity of air, that is, with constant rate of fuel consumption, a higher temperature is obtained under these conditions. A means of measuring the combustibility of coal by determining the volume of its zone of combustion in a furnace of adjustable height is described.

N. E. Rambush, *Production of Bye-Product Producer-Gas under Low Temperature Conditions* (Journal of the West of Scotland Iron and Steel Institute, Session 1922–1923, vol. 30, Part 2, pp. 18–32). The factors concerning the formation of ammonia and tar in gas-producers are discussed, and particulars are given of the design and working results of low temperature gas-producers. To obtain a maximum tar yield, it is not only necessary to have the initial fuel treating temperature low, but the rate of the evolution of the tar must also be considered. In the case of ammonia, it is essential to have a long time factor between the steam and the carbon in the fuel. A producer-gas made under low temperature conditions is not only of high heating value, but is also generated with a high thermal efficiency. A properly designed gas-producer will yield low temperature tar without any special low temperature carbonisation plant being required.

C. Engelhard, *Gasification of Lignite in a Producer* (Zeitschrift für angewandte Chemie, 1923, vol. 36, pp. 98-99). The article describes practice in the production of gas from lignite in a special type of air-blown producer. The fuel bed must be kept at a thickness of about 30 to 40 inches, and requires no stirring of any kind, the grate being flat and stationary.

R. V. Wheeler, *Producer-Gas and Gas-Producer Practice* (Fuel, January-February, March, April, May, June, 1923, vol. 2, pp. 15-21, 48-53, 72-77, 106-110, 156-160, &c.). The author defines the terms "producer-gas" and "gas-producer," and deals generally with the chemical reactions taking place within a gas-producer.

Use of Blast-Furnace and Coke-Oven Gases.—G. B. Bradshaw, *Burning Blast-Furnace Gas* (Blast-Furnace and Steel Plant, April 1923, vol. 11, pp. 250-252). The efficient combustion of blast-furnace gas depends on the type of burner employed. The old-fashioned goose-neck burner, in which the air is drawn in almost entirely by stack draft, is responsible for the general inefficiency of blast-furnace gas combustion in many of the older plants. An improvement on this is the burner where part of the air is aspirated by the gas, but which otherwise depends on the stack draft for supplying air. The most efficient type is the burner designed to aspirate the entire quantity of air by means of gas velocity.

J. Dupuis, *The Utilisation of Coke-Oven Gases in Open-Hearth Steel Furnaces* (Memoir presented to the Liège Congress, June 1922: Revue de Métallurgie, Mémoires, October 1922, vol. 19, pp. 590-599). The temperature of the combustion of the various fuel gases available in an iron and steel works are, on the average, 1850° C. for blast-furnace gases, 2000° C. for producer-gas from coke, 2100° C. for producer-gas from coal, and 2300° C. for coke-oven gases. As an open-hearth furnace requires a gas of a temperature of at least 2100° C., it is obvious that the most economical practice would be to heat such furnaces by means of coke-oven gases, and this has already been done at many works in the United States and in Germany, although systematic attempts really date from 1909, when such gases were first used on a systematic basis at the works of Cockerill at Seraing. In the early stages the coke-oven gases were sent in the ordinary way into the regenerative chambers just as the producer-gas was customarily sent, but it was soon discovered that coke-oven gases became modified in their composition while passing through the chambers, and that a considerable loss in calorific power resulted. Chemical analysis showed that the percentage of hydrocarbons fell, and that the percentage of hydrogen increased, owing to the dissociation of hydrocarbons at the temperatures obtaining in the regenerative chambers. Rich coke-oven gases contain, even after the abstraction of the benzol series, some 2 per cent. of olefines and 25 to 35 per cent. of other saturated hydrocarbons, which constitute more than half the calorific

value of the gases. As olefines dissociate at 600°C . and the saturated hydrocarbons begin to dissociate at 900°C ., carbon deposits were found in the checker work, which reduced the space available for the passage of the gases, and impeded heat exchanges. The experience thus obtained has led to improvements in practice, as it has been found unnecessary to heat such rich gases to the extent necessary in the case of poorer gases of ordinary producer practice, and by using considerably lower temperatures in the regenerative chambers a considerable amount of the calorific value of the gases can be retained for development by combustion, and considerable economy effected. Other practical difficulties met with in the earlier stages have similarly been surmounted, and there is little doubt that, before long, coke-oven gases will be much more widely used in open-hearth practice than they are at present. Experiments at the Saint Jacques works of the Chatillon Commentry Company have given such good results that some of the open-hearth furnaces at these works have been transposed specially for the use of coke-oven gases, and are now using a mixture which is giving excellent results, although necessarily the shape of the ports has had to be somewhat modified.

Coke-Oven Gas in Open-Hearth Furnace (Iron Age, December 14, 1922, vol. 110, pp. 1561–1562). A translation is given of the above paper by Dupuis.

A New Burner for Firing Coke-Oven Gas (Iron and Coal Trades Review, December 29, 1922, vol. 105, p. 977). An illustrated description is given of the general arrangement of the Hunter burner for burning coke-oven gas. The burner is circular in form, and the gas enters from the end and emerges from a series of nozzles of spiral form and set up at a rake. The pressure of the gas induces the air for combustion, and the particular form of the nozzles ensures an intimate mixing of the gas and air. An innovation is the addition of another branch for the supply of blast-furnace gas, either being shut off whilst the other is in service.

Heat of Combustion of Gases.—W. Payman and R. V. Wheeler, *Composition of Gaseous Fuels in Relation to their Utilisation* (Fuel, 1922, vol. 1, pp. 185–196). Though the given calorific values of carbon monoxide and hydrogen are approximately the same, the two gases differ appreciably one from the other as regards the transference of heat from their flames to the body to be heated. The amount of heat radiated from a carbon monoxide flame is nearly $2\frac{1}{2}$ times greater than that from a hydrogen flame. Hence carbon monoxide is preferable to hydrogen as a constituent of fuel gas.

A. G. Witting, *Judging Combustion from Gas Analyses* (Paper read before the Association of Iron and Steel Electrical Engineers; Iron Age, November 16, 1922, vol. 110, pp. 1281, 1332–1333). The author presents a series of formulæ for the determination of the efficiency of the combustion of gaseous fuels by means of waste gas analyses.

F. J. Denk, *Fuel Gas Question in Steel Industry* (Iron Age, February 8, 1923, vol. 111, pp. 401-405, 451). It is shown that dependence cannot be placed on B.Th.U. values in comparing fuels, since it has been found that the efficiency of a gaseous fuel does not depend upon its heat value, but upon its pyrometric efficiency, the amount of waste gases generated and the velocity with which the gases travel over the bath. Combustion curves are shown, which enable the determination and comparison of those gases mostly used in the steel industry and which show that, with the exception of producer-gas, natural gas has the lowest flame temperature of the gases taken into consideration. A table is also given showing the amount of steam which can be raised by the waste gases from one pound of coal gasified. The four fuel gases dealt with are: natural gas, coke-oven gas, producer-gas, and duo-gas, a combination of coal-gas and water-gas.

Utilisation of Waste Heat.—*Utilisation of Waste Heat* (Iron and Coal Trades Review, November 3, 1923, vol. 105, p. 651). Particulars are given of the Kestner boiler adapted for using waste heat gases.

Gas Engines.—D. M. Petty, *Internal Combustion Engines for Power* (Paper read before the Association of Iron and Steel Electrical Engineers: Iron Age, October 26, 1922, vol. 110, pp. 1073-1075). The author outlines the mechanical features and operation of gas engines and Diesel engines and gives some particulars of operating costs.

Large Gas Engines of the Schneider Company (Iron and Coal Trades Review, February 23, 1923, vol. 106, pp. 264-265). An illustrated description is given of the principal features of the Schneider gas engines working on blast-furnace gas.

D. Rauert, *Gas Consumption and Composition of Exhaust Gases from Large Gas Engines* (Stahl und Eisen, October 12, 1922, vol. 42, pp. 1545-1553). The investigation relates to the composition of the exhaust gases at the point of exit from two-cycle gas engines; the composition of the exhaust gas mixture at various points along the exhaust pipe of two-cycle and four-cycle gas engines; the measuring of the gas consumed by a group of four twin two-cycle engines driven by blast-furnace gas, each of 1800 kilowatt nominal output; and the measuring of the gas consumed by a group of four 4-cycle tandem blast-furnace gas engines, each of 1800 kilowatt nominal capacity. On taking samples from the exhaust pipe at different distances from the cylinder, the composition of the waste gases was found to vary considerably according to the distance. The chief variation occurs in the proportions of carbon dioxide, free oxygen and carbon monoxide, and it is thought that the explanation is that the scouring air is at first imperfectly mixed with the exhaust gases and they become more intimately mixed as they flow along the pipe. The measurements of gas consumption were made on four twin double-acting blowing engines driven with blast-furnace gas, the stroke being 1400 millimetres,

and the cylinder diameter 1050 millimetres, and running at 70 revolutions on full load. The actual volume of gas consumed averaged 740 cubic metres per minute, at a temperature of 19.5°C ., and with an average calorific value of 1085 calories per cubic metre. The total heat consumption was determined at 6600 calories per kilowatt hour. Calculations show that the loss in unburnt gas averaged 31.5 per cent., which is chiefly ascribed to the scouring of the cylinder at the end of every stroke. The four-cycle gas engine shows a very considerable advantage over the two-cycle engine in this respect.

VI.—COAL WASHING AND HANDLING.

Coal Washing.—T. Fraser and H. F. Yancey, *Interpretation of Results of Coal Washing Tests* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). Difficulties encountered in the interpretation of the data obtained in coal washing tests are discussed. Methods are given for expressing numerically the relative values of the different operations.

Rheolaveur Washery at the Ormonde Colliery of the Butterley Co., Ltd. (Colliery Guardian, October 27, 1922, vol. 124, pp. 1017–1019). An illustrated description is given of a plant for washing coal by the Rheolaveur process. It is the first of its type on a large scale in this country, and is capable of dealing with 100 tons per hour, screening through coal and washing down 3-inch cubes down to very fines.

L. A. Wood, *Some Aspects of Cleaning Coal by Froth Flotation* (Proceedings of the Cleveland Institution of Engineers, Session 1922–23, No. 1, pp. 13–33). The author describes the principles of the froth flotation process for cleaning coal, and outlines the advantages of the process.

Drying Washed Coal Centrifugally (Iron and Coal Trades Review, April 6, 1923, vol. 106, p. 491). An illustrative description is given of the Simplex continuous centrifugal coal dryer. The machine is installed at the West Ardsley Collieries. The average moisture content of the coal passing to the dryer is 20 per cent., which is reduced to 9.5 per cent. after treatment.

Separation of Coal from Slag.—F. A. Brackmann, *Magnetic Separation of Coal from Slag* (Iron Age, March 22, 1923, vol. 111, pp. 828–829). The dry-magnetic system of separation which is described is based on the fact that the iron pyrites in the coal change into ferric oxide during combustion. The magnetic properties of these oxides, which are bound to the silicates and the lime in the slag, make it possible to separate the latter from the combustible matter by subjecting the residues to the action of highly concentrated magnetic fields. Trials have shown that more than 80 per cent. of the combustible

matter mixed with the slag may be recovered. The burning of this extracted fuel gives an efficiency from 70 to 80 per cent. of the original heating value.

Spontaneous Combustion of Coal.—Marie C. Stopes and R. V. Wheeler, *The Spontaneous Combustion of Coal in Relation to its Composition and Structure* (Fuel, March-April, 1923, vol. 2, pp. 29-41, 83-92). The authors discuss the cause of spontaneous combustion, the banded structure of bituminous coals, and the necessity for differentiating between the various components. The results of a chemical investigation of such coals are reported.

PRODUCTION OF IRON.

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I.—MANUFACTURE OF PIG IRON.

Blast-Furnace Plant and Equipment.—*New Blast-Furnace at Clarence Iron Works* (Iron and Coal Trades Review, January 26, 1923, vol. 106, pp. 111–114). An illustrated description is given of the new blast-furnace and equipment recently installed at the Clarence Iron Works of Messrs. Bell Bros., Ltd., Middlesbrough. The height of the furnace from hearth to top platform is 85 feet, the hearth is 12½ feet in diameter, bosh 21½ feet in diameter, throat 17 feet in diameter, and bell 11 feet in diameter. The furnace is equipped with a battery of seven dust-catchers. The charger is of the Wrightson Ringquist type designed for bucket charging, each bucket having a capacity of 8 tons of ore and limestone or 3 tons of coke. The furnace is served by six Cowper stoves. The gas-cleaner is of the Kling-Weidlein type, and comprises four units each of a capacity of 15,000 cubic feet per minute. Blast is supplied by a Fraser and Chalmers turbo-blower of 25,000 cubic feet at 14 lbs. pressure. The sintering plant has an output capacity of 600 tons of sintered ore in twenty-four hours. There is also a plant for the manufacture of slag bricks.

G. F. Tegan, *New Claire Furnace* (Iron Age, November 30, 1923, vol. 110, pp. 1422–1423). The new Claire furnace of the Reliance Coke and Furnace Co. at Sharpsville, Pa., has a daily capacity of 500 tons. The furnace is served by a double cantilever skip bridge, the feature of which is that its weight is upon its own foundations, rather than upon the stack. The gas is passed through a Brassert gas-washer. Unusual methods are taken for the disposal of the slag. It is granulated and received into a hopper on the suction pipes of low speed centrifugal pumps. It is conveyed as sludge under the Shenango River in 8-inch pipe lines to a storage place, a distance of 1500 feet.

J. D. Knox, *Martin's Ferry Stack is Enlarged* (Iron Trade Review, April 12, 1923, vol. 72, pp. 1081–1084). The reconstructed blast-furnace of the Wheeling Steel and Iron Co., Martin's Ferry, Ohio, is described and illustrated.

Charcoal Blast-Furnace and Wood Distillation Plant of the Mysore

Distillation and Iron Works (Iron and Coal Trades Review, April 13, 1923, vol. 106, pp. 521-522). The plant described was put into operation at the beginning of this year, and is situated on the Bhadra River at Bhradravati. The furnace has a rated capacity of 60 tons of pig iron per day, but the shell has been so designed that the furnace can be enlarged to a capacity of 100 tons per day. It is served by three stoves of the 2-pass side-combustion type. The blowing plant consists of two Mesta single cylinder uniflow engines, each having a capacity of 10,000 cubic feet of air at 4 to 6 lbs. pressure normally, with 12 lbs maximum. The ore at present used is a limonite from Chattanhalli. The permanent source of supply is Kemmangundi, where the ore averages 60 per cent. of iron. The carbonising and distillation plant has a capacity of 240 tons of wood per day. It requires about 4 tons of wood to make the charcoal to produce 1 ton of pig iron.

A. Gradenwitz, *Elevated Intake for Blast-Furnace Air* (Iron Age, December 28, 1922, vol. 110, p. 1700). At the Rombach Iron Works a large air intake has been erected, 138 feet in height, for supplying air to the blowing-engines. A very considerable reduction of moisture in the air is thus obtained, estimated at 35 per cent. So far from being reduced by the friction resistance of the air column drawn in from such a height, the efficiency of the blowing-engines, on account of the lower temperature, greater density and higher concentration of the air (due to the reduction of moisture), is improved in a marked degree.

Mixer Type Hot Metal Cars (Iron Age, February 1, 1923, vol. 111, p. 353). A description is given of a new hot metal car in use at various steel plants in the United States. The ladle consists essentially of a cylinder with two conical ends. Skulling is minimised because of the relatively small radiating surface. The ladle body is designed for tilting in either direction, and the larger sizes are capable of holding an entire blast-furnace cast.

Blast-Furnace Practice.—G. St. J. Perrott and S. P. Kinney, *Combustion of Coke in Blast-Furnace Hearth* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). The results are given of a number of experiments made at eleven blast-furnaces in which the composition of the gases was determined by means of water-cooled gas sampling tubes driven into the hearth through the tuyeres. Combustibility of coke, from the standpoint of its use as blast-furnace fuel, is proportional to the mean rate of gasification per unit volume of the combustion zone. The rate of gasification, other factors being constant, is inversely proportional to the volume of the zone around the tuyeres in which oxygen or carbon dioxide are present. At the wind velocities and temperatures prevailing in the combustion zone of the blast-furnace, it is doubtful whether ordinary metallurgical cokes vary sufficiently in apparent density, porosity, or character of carbonaceous material to influence

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to any great degree the extent of the combustion zone. Analyses of samples of gas taken in the tuyere plane at various points in the hearth at ten blast-furnaces show that oxygen has diminished to practically zero at 24 to 30 inches from the tuyeres, and carbon dioxide has practically disappeared at 32 to 40 inches. The gas analyses indicate that direct reduction of metallic oxides is taking place in the central regions of the hearth. Some difference in the character of the combustion zone at the several furnaces is evident, but no relation is apparent between these differences and the physical properties of the coke. It seems probable that the large differences observed in blast-furnace operation with different cokes are caused by other factors than the relative combustibility of the cokes in the tuyere zone.

G. P. Pilling, *Magnetic Ore in the Blast-Furnace* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923; *Iron Age*, January 11, 1923, vol. 111, pp. 145-148). The author discusses the use of magnetic ore in the blast-furnace, with special reference to the ores of Eastern Pennsylvania and the Adirondack region. Magnetic ore can be divided into three general classes: Fine unsintered or raw ore, raw lumpy ore, and fine sintered ore. As none of these ores contains any appreciable amount of manganese it is necessary to add to the ore mixture material containing this element. Of the three classes of ore mentioned, the least desirable is the lumpy ore. The fine sintered ores are by far the best for blast-furnace use. Correct furnace design, stock distribution, and furnace operation for the three classes of ore are dealt with in detail.

A. Knight, *The Formation and Functions of Blast-Furnace Slags* (*Journal of the Birmingham Metallurgical Society*, vol. 8, No. 6, pp. 209-242).

D. T. Croxton, *Obtaining Large Blast-Furnace Production* (*Iron Age*, March 29, 1923, vol. 111, pp. 897-900; *Iron Trade Review*, April 5, 1923, vol. 72, pp. 1009-1013). The operating records are given of the Trumbull-Cliffs Furnace with reference to the use of scrap and hard ore combined with fast driving. From the results it is concluded that the use of non-magnetic hard crushed ore, up to 2½ inches in size, does materially assist the operation of fast driving, and that the use of scrap up to 5 per cent. of the product produced requires very little, if any, extra fuel.

A. H. A. Robinson, *Titanium* (Canada, Department of Mines, Mines Branch, Ottawa, 1922). This report includes information on the smelting of titaniferous magnetites in the blast-furnace and electric furnace. Typical analyses are given of ferro-titanium, and the use of titanium in steel metallurgy is briefly dealt with.

P. Lemoine, *The Fast Driving of Cowper Stoves by the Pfoser-Strack-Stumm Process* (*Revue de Métallurgie, Mémoires*, February 1923, vol. 20, pp. 88-94). The number of Cowper stoves employed per blast-furnace varies considerably, the most frequently occurring combination being four, of which one is driven and the other three used for heating.

When cleaning is necessary, two stoves only can be used for heating, and both the period of the heating and the temperature of the blast is diminished. Four stoves represent, however, a considerable capital expense, besides occupying valuable space. On examining a thermal balance sheet relating to a battery of four stoves, it would be found that, taking 26 per cent. as lost with the gases, and 18 per cent. lost by radiation, only 56 per cent. of the heat remains available, and many attempts have been made to improve the efficiency from this point of view. The Pfoser-Strack-Stumm process, which was commenced at Neunkirchen, and having given satisfactory results was patented in 1913, may be briefly described as follows:

It consists of increasing the rate of the passage of the products of combustion in a Cowper stove, in order to obtain, without any increase in the temperature of the waste gases, either a diminution in the period of heating or, given equal periods of heating, an increase in the blast temperature, or both results simultaneously. The rate at which the products of combustion are driven through being carried to an extent that no appreciable increase in the temperature of the waste gases can take place, this being achieved by the special arrangement of the refractory bricks, and by the accessory installation of blowing appliances and fans. In order to obtain full advantage of the improvement suggested, the interior arrangements of the stove have to be considerably modified; the old air inlets being closed up, and the air being introduced by means of a special tube into the centre of the stove straightaway. The process relies on the economy of 14 per cent. of the gases, but its greatest advantage lies in the possibilities of dispensing with some of the stoves; indeed, the most recent installations consist of only two stoves. Instead of the ordinary hexagonal bricks being used, special octagonal bricks with much smaller circular apertures are employed, and a table is given showing the dimensions and arrangements of these bricks. At the No. 2 furnace of the Neunkirchen works two stoves have been installed, one fitted with hexagonal bricks, and the other with octagonal bricks. The first named, which is 30 metres in height, gives a flue temperature of 131°C . at the end of the heating period, and the fall in temperature of the blast is 96°C . per phase, whereas, in the second stove, which is only 25 metres in height, but is fitted with octagonal bricks, the flue temperature is only 78°C ., and the fall in the temperature of the blast is 84°C ., an example which shows effectively the advantages of using octagonal bricks. (See also this Journal, 1914, No. II. p. 232).

Cosmo Johns, *Oxygen and Metallurgical Processes* (Paper read before the Faraday Society, October 16, 1922). The author reviews the possibilities in the use of oxygen enriched air in the metallurgical processes.

Blast-Furnace Gas Cleaning.—F. E. Kling, *The Trend in Blast-Furnace Gas Cleaning* (Blast-Furnace and Steel Plant, January 1923,

vol. 11, pp. 44-46). The advantages of dry-hot cleaning over wet-cold cleaning of gas are chiefly that the sensible heat of the gas is retained, that no water is required, and consequently no settling basins, thereby saving in ground space; the labour costs in handling the dust are less, and the dust can be sintered and briquetted immediately, while sludge from the wet process has to be dried. The comparative first cost, ground space, and power required, and cost of cleaning are given for a Halberg-Beth plant and a Kling-Weidlein plant, with a capacity of 3,500,000 cubic feet per hour. The first cost and cost of operation of Kling-Weidlein plant are much the lower, but the degree to which the gas is cleaned is much higher in the Halberg-Beth, being 0.004 grain as compared with 0.3 grain of dust per cubic foot in a single stage Kling-Weidlein and 0.1 grain in a two-stage cleaner.

K. Wiest, *Separation of Dust by Gravity* (Stahl und Eisen, November 2, 1922, vol. 42, pp. 1650-1653). In most dust-cleaning apparatus, the principle of gravity plays some part in helping to precipitate dust particles from the gases in which they are entrained. The author has worked out formulæ for calculating the rate at which dust particles fall, and formulates rules for the design of dust chambers. The provision of sufficient floor space in the chamber is the important factor.

Flue-Dust Briquetting.—A. L. Stillman, *Flue-Dust Briquetting by Corrosion Process* (Iron Age, December 14, 1922, vol. 110, pp. 1571-1572; Iron Trade Review, November 9, 1923, vol. 71, pp. 1291-1292). The corrosion process of briquetting blast-furnace flue-dust has been adopted by the Hanna Furnace Co., Buffalo. The term corrosion is used because an acid agent acts upon the iron monoxide in the flue-dust with corrosive effect, forming iron sesquioxide. The usual corrosive agent is wire-mill liquor or a solution of copperas. One part of copperas crystals, 9 parts water, 45 parts fresh flue-dust, and 45 parts old flue-dust is a typical briquetting mixture. These ingredients are thoroughly mixed, ground, and pressed. The iron sesquioxide formed is a dense hard waterproof binder.

Electric Smelting of Iron Ore.—A. Stansfield, *Iron Ore Smelting by Electricity* (Paper read before the Association of Iron and Steel Electrical Engineers: Chemical and Metallurgical Engineering, November 8, 1923, vol. 27, p. 941). Some of the difficulties in the electric smelting of Canadian ores are outlined. The Electrometall furnace developed in Sweden is practically the only furnace in successful commercial operation, but iron ores can be smelted successfully in the Noble furnace at Heroult and even in plain, open-top pit furnaces, and these latter furnaces are preferable to the Swedish furnace for the production of grey foundry iron.

L. Lyche, *The Production of Foundry Pig Iron in the Electric Furnace* (Stahl und Eisen, January 25, 1923, vol. 43, pp. 110-116). The article describes an electric furnace of special type constructed during

the war by the Arendal Smelteverk, at Arendal in Norway, for the smelting of foundry pig. The furnace consists of two low open stacks side by side on a concrete base, the internal diameter being about 9 feet and the height 3 feet 4 inches. The ore, obtained in the immediate neighbourhood, contained 71.01 per cent. ferric oxide with phosphoric acid 0.83, and sulphide of iron 0.53 per cent. The charge was in the proportion of 100 kilogrammes ore to 13 kilogrammes limestone, 27 kilogrammes coke and 2 kilogrammes apatite, each charge containing about 4.5 tons of ore and the other materials in proportion. The kilowatt-hour consumption per ton of pig iron produced averaged about 3000. For successful working a high temperature, an excess of carbon, and long melting time are necessary. The production averaged 10 to 15 tons of pig iron per day with a composition of: carbon, 3.80; silicon, 2.50; manganese, 0.35; phosphorus, 0.60; sulphur, 0.04 per cent. At the end of 1918 the furnace was shut down, after giving a total output of 4500 tons of pig iron.

Synthetic Pig Iron.—C. E. Williams, C. E. Sims, and C. A. Newhall, *Electric Furnace Detinning and Production of Synthetic Grey Iron from Tinplate Scrap* (Paper read before the American Electrochemical Society, May 1923). Experiments were conducted in a small electric furnace in which tinplate scrap was melted with various addition agents in attempts to remove the tin from the iron. Sodium chloride, iron sulphide, and an oxidising slag were used under various conditions. The conclusions reached were that in the electric furnace complete detinning is impossible, and any detinning impractical. No tin is volatilised, ordinarily, when iron scrap containing it is melted in the electric furnace. Melting tests conducted in a cupola showed that the amount of detinning was dependent upon the amount of surface of metallic tin exposed to the oxidising gases. This may be as much as 50 per cent. in some cases, whereas in others it may be practically nil. Lead can be removed completely from lead-coated iron, and zinc can be largely removed from galvanised scrap in the electric furnace. Tests-bars, prepared by melting pig iron with various quantities of tin, were subjected to physical tests. The results showed that a tin content of 1 per cent. or less did not seriously affect the properties of grey iron. Synthetic cast iron made from tinplate scrap was used successfully in making commercial castings of good quality.

M. Didier, *Synthetic Pig Iron* (Fonderie Moderne, December 1922, vol. 15, No. 12).

Manufacture of Ferro-Alloys.—L. Jordan and F. E. Swindells, *The Decarburisation of Ferro-Chromium by Hydrogen* (U.S. Bureau of Standards, Washington, 1922, Scientific Paper No. 448). The recently developed rustless iron may be considered as a stainless steel from which the carbon has been largely eliminated, the carbon content of

rustless iron being about 0.1 per cent. or somewhat lower. In order to produce an iron alloy containing as high as 12 per cent. chromium and still keep the carbon content low as indicated, it is necessary to use carbon-free ferro-chromium. Such an alloy made by aluminothermic methods is available, but at prices too high to allow its extended use in producing rustless iron. The decarburisation of ferro-chromium by means of hydrogen has been suggested. Tests carried out on 60 per cent. ferro-chromium containing 8 per cent. carbon showed that there was a slow decarburisation of the powdered ferro-alloy by dry hydrogen between 1100° and 1350° C. The removal of the carbon was more rapid just above than just below the melting point of the alloy. The most rapid decarburisation was secured by passing a stream of hydrogen through molten ferro-chromium at approximately 1500° C. Under these conditions nearly 1 per cent. of carbon was removed from the alloy in four minutes, as compared with four hours required to reduce the carbon 1.6 per cent. at a temperature just below the melting point of the alloy. The most promising condition for refining high-carbon ferro-chromium by this method is probably blowing the molten alloy with a blast of hydrogen in a converter.

F. A. J. Fitzgerald, *Ferro-Alloys and Hydroelectric Power* (Iron Age, January 4, 1923, vol. 111, pp. 24-25). The author discusses the relation between the manufacture of ferro-alloys and hydroelectric power developments in the United States.

B. Waeser, *Commercial Electrothermic Process* (Chemiker Zeitung, 1922, vol. 46, pp. 928-930, 947-948, 970-972). The use of electric furnaces for melting and manufacturing iron and ferro-alloys are briefly surveyed.

B. D. Saklatwalla and A. N. Anderson, *Improvements in Ferro-Alloy Electric Furnaces of High-Power Input* (Paper read before the American Institute of Electrical Engineers, April 1923). The paper deals with the efficiency of power input in ferro-alloy furnaces and discusses the electrical factors to be considered in the design of the leads for achieving such efficiency. It also describes a new system of regulation whereby the furnace temperature is kept constant by keeping the energy input constant by means of true watt regulation. Several factors in the design and construction are discussed.

B. D. Saklatwalla and A. N. Anderson, *Electric Furnace Makes Ferro-Vanadium* (Electrical World, February 24, 1923, vol. 81, No. 8). Particulars are given of a new process for the reduction of vanadium by means of carbon. A new design of furnace is used having three graphite electrodes.

E. F. Russ, *A New Electric Furnace for Producing Alloys* (Stahl und Eisen, January 25, 1923, vol. 43, pp. 116-118). The furnace is in the form of a drum mounted on rollers so that it can be rotated, and it is equipped with three electrodes, fitted in such a manner that the chamber of the furnace is made air-tight.

Iron Industries of Various Countries.—R. Dunn, *An Iron and Steel Industry for British Columbia* (Canadian Mining Journal, December 29, 1923, vol. 43, pp. 896–897). Investigations by an expert into the possibility of establishing an iron and steel industry in British Columbia have led to the conclusion that the conditions are highly favourable for the immediate erection of a new plant. The most suitable spot would be on the Fraser River. Coking coal, various kinds of iron ore, and limestone of good quality all abound within reasonable distance. There are also abundant waterfalls from which hydroelectric power could be derived.

J. V. MacCartney, *The Indian Iron and Steel Industry and its Probable Development* (Blast-Furnace and Steel Plant, February 1923, vol. 11, pp. 140–144). A brief review is given of the growth of the iron and steel industry in India. The economic conditions are extremely favourable for the cheap manufacture of high grade iron and steel products.

Mining in South Africa (Mining Journal, October 28, 1922, vol. 139, pp. 804–806). In a leading article on the position of the mining industry of South Africa in 1921, reference is made to the development of enterprises concerned with the manufacture of iron and steel. Altogether 20,000 tons of iron and steel were produced in the Union in 1921. The principal undertaking is the Union Steel Corporation of South Africa, which has installed a 25-ton open-hearth furnace and a 22-inch mill. An amalgamation of the Corporation with the South African Iron and Steel Corporation has been effected, and plans are under consideration for a plant to manufacture 75,000 tons of steel yearly. The Dunswart Iron and Steel Works aim at producing 500 tons of electric steel per month, and the Witwatersrand Co-operative Smelting Works are projecting a plant with an output of 4500 tons of steel per month. The Newcastle Iron and Steel Works and the Transvaal Blast-Furnace Company were inactive in 1921.

H. Cole Estep, *What is Happening in the Ruhr?* (Iron Trade Review, March 8, 1923, vol. 72, pp. 727–733). The economic situation in the Ruhr district and the influence of the French occupation are dealt with. A complete list is given of the blast-furnaces and steelworks in this district, showing names of individual firms, numbers of furnaces and their capacity.

L. W. Hoyt, *Producing Iron and Steel in China* (Iron Trade Review, January 18, 25, 1923, vol. 72, pp. 227–230, 303–305). The author deals with the present situation in the iron and steel industry of China. The manufacture of iron and steel can be conveniently separated into three distinct groups, namely, the Hankow district, the Peking or Chihli district, and the Mukden or Manchuria district. The outputs of both pig iron and finished rolled products are far below the available capacity, owing to the inferior grades of raw material and high operating costs. The operations of the Han-Yeh-Ping Iron and Coal Company, which owns the largest plant in China, and the Yangtse

Engineering Company are described, and particulars of costs are given.

P. F. Kohlhaas, *First Modern Blast-Furnace in North China* (Blast-Furnace and Steel Plant, January, 1923, vol. 11, pp. 37-43). The Lungyen Mining Administration has completed its new 250-ton blast-furnace at its establishment about 11 miles west of Peking. The entire plant is of American design. The supply of iron ore is furnished by the mines at Hsuanhwa in the Kalgan region, about 110 miles to the north, and a good coking coal is at present obtained from mines about 300 miles to the south. A general description, with illustrations of the plant, is given.

H. C. Huggins, *Japan's Iron and Steel Industry* (Far Eastern Review; Iron and Coal Trades Review, May 4, 1923, vol. 106, p. 641). Particulars are given showing the number of blast-furnaces owned by the principal pig iron producers in Japan, and their capacity. Figures giving the production of pig iron and steel shapes during the period 1914-21, and the manufacturing capacity in pig iron and steel, are also included.

J. Horton, *British Ferro Trade Surveyed* (Iron Trade Review, May 24, 1923, vol. 72, pp. 1527-1530). The development of the ferro-manganese industry in this country is dealt with, and tables are given showing typical analyses, output, and exports of ferro-manganese. There are nineteen furnaces producing ferro-manganese out of a total of 478 blast-furnaces.

Costs of Iron Manufacture.—P. M. Tyler, *Foreign and Domestic Pig Iron Costs* (Iron Age, February 15, 22, March 1, 1923, vol. 111, pp. 467-470, 533-536, 605-606). The author has collected a great deal of information regarding the cost of manufacturing pig iron in Britain, United States, Belgium, and Lorraine. The disadvantageous position of the United States in respect of costs is pointed out.

E. H. Lewis, *Presidential Address* (Journal of the West of Scotland Iron and Steel Institute, Session 1922-1923, vol. 30, pp. 3-7). Interesting particulars are given regarding the costs of iron and steel production during 1912-1921.

Classification of Pig Iron.—H. H. Shepherd, *The Grading of Pig Iron* (Foundry Trade Journal, January 11, 1923, vol. 27, pp. 25-26). The composition of pig iron is not in itself an absolutely reliable means of grading, but by a combination of the analytical and fracture methods it is possible to evolve a system of grading that is reliable and scientific.

American Methods of Sampling Pig Iron (Foundry Trade Journal, December 21, 1923, vol. 26, pp. 515-516). The appliances and methods adopted by the Carnegie Steel Company for sampling molten metal from the blast-furnace, and pigs from truck or stock pile, are described.

II.—DIRECT PROCESSES.

Direct Production of Iron and Steel.—R. Whitfield, *Production of Iron and Steel Direct from the Ore* (Iron and Coal Trades Review, January 5, 1923, vol. 106, pp. 6–7). The author discusses the Bourcoud system of direct production. The solution of the gas production problem is in every way different from accepted practice. To obtain the requisite intimate mixture of air and fuel, the latter is pulverised and the air is preheated to from 400° to 800° C., the combustion of the fuel in the heated air ensuring the practically immediate formation of CO_2 . By permitting a regulated amount of excess carbon to pass the combustion zone, and by causing the mixture of heated CO_2 and carbon to traverse the passages of a chamber of sufficient length and cross-sectional area, the necessary period of time-contact of CO_2 and carbon is obtained, whereby the whole of the CO_2 is converted to CO. The application of the reducing gas, possessing a leaving temperature of 1000° C. to the ore merits careful consideration. The reduction furnace is of the rotary type, wherein the gases have a movement more or less continuous about the axis of the furnace.

K. Klöpper, *The Bourcoud Process* (Stahl und Eisen, March 22, 1923, vol. 43, pp. 400–402). The description of the Bourcoud process, previously published (Iron Trade Review, August, 11, 1921, vol. 69, pp. 363–368), appears in translation, with some criticisms concerning the technical details of the process, and it is pointed out that the results claimed are not sufficiently supported by practical calculations.

Manufacture of Electrolytic Iron.—F. A. Eustis and C. P. Perrin, *Electrolytic Iron and Sulphide Ores* (Paper read before the Mining and Metallurgical Society of America: Chemical and Metallurgical Engineering, October 4, 1922, vol. 27, pp. 684–685). Reference is made to the production of boiler tubing electrolytically by the Société Le Fer, Grenoble, France, and to cores from powdered electrolytic iron and zinc dust, made at the only works in America producing the material, the Western Electric Company, Hawthorn, Illinois, where it is used in telephone plant. Experiments are then described in the manufacture of electrolytic iron from pyrites. The reaction involved is in the first place $2\text{FeCl}_2 + \text{FeS} = 3\text{FeCl}_2 + \text{S}$, the reaction being exothermic, and thus producing the hot solution required for the electrolysis stage. The by-product of the reaction just noted is pure flower of sulphur, which at present market prices is of more value than the ultimate product. Any copper present goes into solution and can cheaply be recovered. In electrolysis graphite anodes are employed, the iron being deposited from the chloride solutions in the cathode compartment. The solution is never allowed to become sufficiently concentrated to give rise to trouble from the evolution of free chloride. The power cost of the operation is not more than 5 dollars per ton,

which compares favourably with coke costs in blast-furnace practice. The forecast is made that, in view of the vast supply of pyrrhotite available, and the value of the sulphur obtained as a by-product, the process has great possibilities and a promising future before it. Capital charges, for plant &c., are estimated at 8 to 12 dollars per ton capacity. The sulphur production is roughly equivalent to one-half of the iron production by weight.

History of Iron and Steel.—B. Neumann, *Roman Iron* (Zeitschrift für Elektrochemie, April 1923, vol. 29, pp. 175–179). A number of specimens of tools and weapons of Roman manufacture have been chemically and metallographically examined, and the analyses and micrographs are published. A razor blade and certain other implements afford evidence that they were made from soft iron blooms which were afterwards carburised in order to harden them.

Rhys Jenkins, *Early History of Steel Making in England* (Paper read before the Newcomen Society, November 29, 1922: Engineer, December 1, 1922, vol. 134, pp. 572–574). The history of the production of steel in England before Huntsman's invention of cast steel is very scanty and does not seem to have been the subject of much research. The paper by the present author throws some light on the beginnings of the industry in this country, and much information has been collected from obscure records and little-known documents, and is now made available for the first time to students of the subject.

The earliest definite reference to the production of steel, found by the author, is quoted in the "Victoria County History of Sussex," where it is mentioned that John Glande in 1513 held a tenement called "a Forge of Steel" in Ashdown Forest, Sussex. In 1525 this forge came into the hands of John Bowley, who still held it in 1548.

FOUNDRY PRACTICE.

Cupola Practice.—E. A. Roper, *Foundry Cupolas* (Foundry Trade Journal, October 19, 1922, vol. 26, pp. 321–323). Various details in cupola design and their effect on cupola operation are discussed. Stress is laid upon the introduction of the blast to the bed, and the volume and pressure of blast at which the cupola is expected to work.

New Development in Cupola Construction (Iron Age, October 19, 1922, vol. 110, pp. 991–992). A translation is given of an article by E. Hellmund (Die Giesserei, 1922, No. 18), describing the Schürmann cupola. The blast is preheated by being passed through a chamber fitted with chequer brick, the waste gases from the cupola passing through a similar chamber, reversals being carried out every ten minutes. The time of melting is shortened and the amount of coke required is reduced to 6·5 to 7·5 per cent. depending on the kind of castings required. In addition to the saving of coke the quality of the iron is improved due to the lowering of the sulphur by 20 to 30 per cent. The temperature of the waste gases leaving the chimney stack is about 100–150° C. The results are given of operating tests.

C. Rein, *Coke Consumption in Cupola Working* (Giesserei-Zeitung, October 31, 1922, vol. 19, pp. 629–634). The consumption of coke is shown to be dependent upon the quality of the coke and the iron, the service of the cupola and its design. The working results of a cupola without preheating of the blast are compared with those of a Schürmann cupola in which the blast is preheated. It is shown that, though some saving of coke is effected by preheating, it is just about counterbalanced by the loss of iron due to burning.

F. J. Cook, *Cupola Receivers* (Paper read before the Institution of British Foundrymen: Foundry, January 1, 1923, vol. 51, pp. 27–30). The general arrangement of the different types of cupola receivers is shown. An improved form of cupola in which the receiver forms the bottom part, has the former distinct and separate from the cupola body, thus enabling it to be withdrawn for clearing. A recently introduced receiver of the outside type is fitted with oil jets for superheating.

H. H. Shepherd, *Foundry Cupola Tuyeres* (Metal Industry, January 5, 1923, vol. 22, pp. 11–12). The correct ratio of tuyeres to cupola area and number and position of tuyeres are briefly discussed. The use of spiral or double row tuyeres is also dealt with.

E. A. Roper, *Methods of Cupola Blowing Compared* (Foundry Trade Journal, March 8, 1923, vol. 27, pp. 196–197). The essential difference

between the fan blower and the Roots blower is described, and their efficiency is discussed.

Devise Flexible Charging System (Foundry, April 1, 1923, vol. 51, pp. 276-279). An illustrated description is given of the equipment and methods of handling materials and cupola charging employed at a large foundry in the United States.

R. Buchanan, *The Foundry Cupola* (Paper read before the Sheffield Foundry Trades Technical Association: Foundry Trade Journal, January 4, 11, 18, 1923, vol. 27, pp. 9-13, 27-28, 41-42). A general discussion on cupola practice.

J. Grennan, *Visual Observation of Melting in a Cupola* (Paper read before the American Foundrymen's Association, May 3, 1923). The author discusses conditions in a cupola as observed through holes cut through the cupola shell. The condition of the coke and iron during the melting process is recorded.

Some Notes on Cupola Practice, with Special Reference to Tap Holes (Foundry Trade Journal, May 31, 1923, vol. 27, pp. 445-446).

S. J. Felton, *Theories on Cupola Reactions* (Foundry, May 1, 1923, vol. 51, pp. 351-352). The work of previous investigators on the melting zone and temperatures in the cupola is reviewed.

General Foundry Practice.—P. Longmuir, *British Foundry Practice* (Paper read before the American Foundrymen's Association: Iron Trade Review, May 17, 1923, vol. 72, pp. 1459-1461). The author reviews metallurgical developments in foundry practice in this country.

H. L. Campbell, *Modern Methods for Making Cupola Mixtures* (Chemical and Metallurgical Engineering, March 14, 1923, vol. 28, pp. 492-495). The proper proportioning of pig iron mixtures to secure castings of required composition is described, and several charts are given for calculating different mixtures.

S. B. Phelps, *Comparison of Sand-Cast and Machine-Cast Pig Iron* (Blast-Furnace and Steel Plant, March 1923, vol. 11, pp. 196-197). Owing to the slower cooling of sand-cast pig iron most of the carbon separates as graphite, whereas chilled pig retains the carbon in the form of combined carbon, and this fact influences the melting point. Machine-cast pig undoubtedly melts at a lower temperature than sand-cast pig of similar analysis. A mixture of both kinds of pig in the same cupola charge will not give such uniform results as a mix made from one type of pig, but a mixing ladle, forehearth, or the holding of a reasonable quantity of metal in the cupola before tapping will give a more uniform iron when one type of pig cannot be exclusively used in the mixtures. Chilled pig is to be preferred to sand-cast pig, if only to avoid the excess slag produced from the sand clinging to the pigs.

H. B. Swan, *Notes on Grey Iron for Automotive Castings* (Paper read before the American Foundrymen's Association, May 3, 1923: Iron Trade Review, May 17, 1923, vol. 72, pp. 1455-1458). As the result of questionnaires sent out to American foundries the author has collected

data on iron mixtures and cupola practice in the production of motor-car castings. The effect of carbon and other elements on the physical properties of these castings is reviewed, and practice at the various foundries is compared.

Briquetting Cast Iron Borings (Iron and Coal Trades Review, March 9, 1923, vol. 106, p. 341). Illustrated particulars are given of the "President" press, which is designed for mechanical operation. The working load is 250 tons, but by the adoption of a toggle lever with knuckle joints the press can be made to exert a pressure up to 300 tons. The briquettes produced are 3 inches in diameter.

R. Moldenke, *The Desulphurisation of Cast Iron* (Paper read before the American Foundrymen's Association, May 2, 1923). The use of soda ash for the desulphurisation of cast iron, a method developed by Walter, is described.

F. Wüst and P. Stühlen, *Influence of the Arrangement and Number of Runners on the Solidification and Strength Properties of a Casting* (Mitteilungen a.d. Kaiser-Wilhelm Institut für Eisenforschung, 1922, vol. 4, pp. 145-163). Cooling curves were taken of bars of 30, 40, and 50 millimetres diameter respectively, and these show differences according to the arrangement and number of runners provided for pouring. In the neighbourhood of the runner the rate of cooling is delayed, but the influence of this on the amount and on the formation of the graphite could not be detected. By the provision of a number of runners the rate of cooling of the casting was rendered uniform. In thin-wall castings the transverse and tensile strength and the ball hardness increased by increasing the number of runners. In thicker castings no difference in the tensile properties due to increasing the number of runners was noticeable, but in the neighbourhood of the runners the tensile values were found in all cases to be lower than in those parts farther removed from the runners. With a suitable arrangement of runners the tensile properties of a test-piece machined out of the casting itself are invariably superior to those of separate bars cast simultaneously from the same ladle.

E. Longden, *Gating, Feeding, and Casting* (Paper read before the Institution of British Foundrymen: Foundry Trade Journal, December 7, 14, 21, 1922, vol. 26, pp. 471-472, 489-490, 509-512). A general review is given of the methods of pouring, feeding, and casting, with special reference to grey cast iron.

E. V. Ronceray, *Facts about Sound Castings, Feeding Heads, Runners, and Venting* (Paper read before the Institution of British Foundrymen: Foundry Trade Journal, April 12, 1923, vol. 27, pp. 289-294).

S. J. Felton, *Study of Pouring Temperatures* (Foundry, February 15, 1923, vol. 51, pp. 138-140). The author has studied the temperature drop in molten cast iron, using different pouring methods and arrangement of moulds.

H. K. Briggs, *Pouring Temperatures of Steel Castings* (Transactions of the American Society for Steel Treating, May 1923, vol. 3, pp. 851-

854). The effect of varying pouring temperatures on the physical properties of castings is discussed.

R. Burke, *Converter Produces Better Steel* (Iron Trade Review, December 7, 1922, vol. 71, pp. 1555-1556, 1563). Steel-making practice in small converters for the production of castings is discussed. The usual deoxidisers used are ferro-manganese and ferro-silicon. The addition of aluminium is not necessary or desirable. The determining factor in the production of steel of good quality is cupola operation.

J. E. Hurst, *Internal Chill in Castings* (Foundry Trade Journal, February 1, 1923, vol. 27, pp. 85-87). The phenomena of internal chill can be attributed to the lag or period of time which elapses in the cooling down of cast iron before the maximum rate of cooling is attained. If this maximum rate of cooling is delayed, owing to low initial temperature, until the temperature zone of the formation of the major portion of the graphite is passed, then if the composition of the iron is such as can be described as "bordering on chill" the outer layers will solidify grey and the internal layers white. The influence of segregation phenomena has not been forgotten, and such phenomena in themselves, if of sufficient magnitude, would also be sufficient to explain the production of internal chill. Many cases of internal chill are known where segregation phenomena cannot account for this condition. Artificial alteration of the rate of cooling during the solidification of the metal can also be utilised for the production of internal chill.

O. Smalley, *Volume Changes of Cast Iron on Solidification* (Paper read before the Institution of British Foundrymen: Foundry Trade Journal, February 1, 1923, vol. 27, pp. 89-99). The author gives the results of a series of experiments on the volume changes of various cast irons on solidification and considers the principal factors controlling liquid shrinkage, namely, pouring temperature, rate of solidification, and chemical composition.

The Influence of Dissolved or Occluded Gases in Cast Iron (Foundry Trade Journal, March 15, 1923, vol. 27, pp. 209-211). A review of the work of previous investigators.

F. Wüst and G. Schitzkowski, *Influence of Some Impurities on the Shrinkage of Cast Iron* (Mitteilungen a.d. Kaiser-Wilhelm Institut für Eisenforschung, 1922, vol. 4, pp. 105-124). Various devices have been used for the measurement of the contraction of cast iron as it cools in the moulds, and the authors preface the account of their investigations with illustrated descriptions of the apparatus devised by the following: W. J. Keep, who studied the influence of various elements on the contraction, without, however, recording the temperatures as the metal cooled; T. Turner, who took temperature-time curves and studied four classes of pig iron and the influence of silicon; F. Wüst's hydraulic apparatus; T. D. West, who studied the influence of cross-section on the amount of contraction; and

A. Diefenthaler, who also investigated the influence of silicon. The authors constructed an apparatus of new design, which automatically recorded both the contraction and the time-temperature curves, and with the aid of this they first determined the contraction of commercially pure iron with increasing percentages of carbon. For pure iron (with carbon = 0.08, phosphorus = 0.01, sulphur = 0.002) the contraction was found to be 2.39 per cent., the casting temperature being 1380° C. The effect of carbon up to 1.7 to 2 per cent. is to lower the contraction, which reaches a minimum of 1.9 per cent., and then increases slowly with higher carbon percentages. Phosphorus has much the same effect as carbon, the contraction diminishing to 1.3 per cent. with phosphorus at 1.7 per cent. and increasing again with higher phosphorus. In both series of irons the values found for the contraction have a definite relation to the phase diagram. The formation of mixed crystals reduces the contraction, but as soon as the limit of solubility is passed, and iron carbide (ledeburite) or iron phosphide, as the case may be, is associated with the mixed crystals the contraction increases. In the iron carbon alloys the pre-pearlitic contraction alone changes with changing carbon content, but after passing the pearlite point the contraction is independent of the carbon concentration, and from that point onwards amounts to about 1 per cent. Silicon, except in quite small amounts, reduces the contraction, and it falls from 2.39 to 1.7 per cent. when a percentage of 18.24 silicon is reached. Among the elements investigated, manganese is the only one which raises the contraction. At 15.49 per cent. manganese, it had risen to 2.89 per cent. Sulphur up to 1 per cent. has a strong effect in lowering contraction, and at higher percentages the lowering effect is continued, but much less strongly. Both nickel and chromium lower the contraction, but not to any very appreciable extent.

J. W. Bolton, *Graphite in Cast Iron* (Paper read before the American Foundrymen's Association, May 1923: Foundry, May 15, 1923, vol. 51, pp. 405-407). The author deals with the quality of materials as an important factor in the production of castings. The size of graphite flakes has great influence on the quality.

R. Moldenke, *Grey Iron Castings: Their Chemical Analysis* (Canadian Foundrymen: Foundry Trade Journal, November 2, 1922, vol. 26, pp. 367-369). Some considerations regarding the chemical composition of castings are discussed and a table is given showing recommended analyses for castings for different purposes.

J. E. Fletcher, *Surface and Internal Defects in Iron Castings* (Paper read before the Institution of British Foundrymen: Foundry Trade Journal, March 8, 22, 1923, vol. 27, pp. 200-201, 236-237). The relationship, cause, and prevention of surface and internal defects in cast iron are discussed.

H. Cole Estep, *How Quality is Produced under Quantity Production Conditions* (Paper read before the Institution of British Foundrymen: Foundry Trade Journal, December 7, 14, 21, 1922, vol. 26, pp. 459-

461, 481-484, 504-506). The author discusses the production of high quality castings in large quantities, with special reference to American practice.

G. A. Drysdale, *Strong Iron made without Steel* (Foundry, May 1, 1923, vol. 51, pp. 375-376). The use of steel scrap is not essential for making castings with high physical properties, as this can be attained by the use of suitable pig irons in the cupola mixture, and carrying large percentages of cast iron or return scrap. Suitable mixtures for this purpose are given.

H. R. Simonds, *Cleaning Steel Castings* (Foundry, May 1, 1923, vol. 51, pp. 345-350). The application of gas cutting apparatus for the removal of headers from castings is described.

W. Kaempfer, *Efficiency of Sand-Blasting* (Stahl und Eisen, March 29, 1923, vol. 43, pp. 425-430). Some notes are given on the design of nozzles for sand-blast machines, the power absorbed, the size of sand and the economies obtained compared with cleaning or scaling by hand.

J. A. Rathbone, *Centrifugal Casting of Iron Piston Rings* (Paper read before the American Foundrymen's Association, May 2, 1923). Economy by making castings by the centrifugal method is entirely dependent on the size of the castings and the cost of replacing the moulds.

L. Cammen, *Centrifugal Casting* (Paper read before the American Foundrymen's Association, May 3, 1923). The author traces the history of the centrifugal casting process, and discusses its practical application and possibilities. He also describes the method devised by himself for hot-mould centrifugal casting.

H. Baclesse, *Casting of Acid-Resisting Iron* (Giesserei Zeitung, March 1, 1923, vol. 20, pp. 103-106). In the casting of high silicon iron for acid-resisting ware, the separation of the graphite causes considerable difficulty. For the melting and working of such material the electric furnace is much more suitable than the cupola.

J. Longden, *Some Casting Problems of Acid-Resisting Iron* (Paper read before the Institution of British Foundrymen, December 7, 1922: Foundry Trade Journal, December 7, 1922, vol. 26, pp. 466-470). The author describes practice in the melting and casting of a high silicon cast iron. The alloy is melted in the cupola, though rather lighter charges are used than in the case of cast iron. Before being used for castings the metal is run down and then remelted. The raw materials used are wrought iron and steel scrap, scrap from the same alloy, and ferro-silicon pig. In calculating the charges, an allowance is made for loss of silicon of 0.5 per cent. Two cupolas are in use, of 18 inches and 30 inches diameter respectively, the latter having a receiver. A very considerable difference is noticeable between the molten metal as it leaves the smaller cupola and that leaving the receiver of the larger. The metal from the small cupola soon becomes covered with a mass of shining particles of graphite. The metal in the ladle

is skimmed and poured. On completion of the casting operation the ingot has another deep cover of graphitic matter. This is skimmed off, but black patches soon appear, until the surface is again nearly covered. The ingot, when broken across anywhere along its length, shows pockets full of graphitic flakes. This factor is a frequent cause of scrap castings. The metal from the larger cupola has a blast of air blown through it while in the receiver, the intention being to burn out carbon as in converter practice. Silicon is also oxidised at the same time. In this case the separation of graphite has proceeded rapidly in the receiver. Not much graphite of the shiny flaky kind comes to the surface, but instead a graphitic kish appears, which very soon forms a heavy crust on top of the metal. Though the tendency for separated graphite to appear is less in the case of the metal from the larger cupola it still remains a serious difficulty, pockets and fissures full of graphite frequently being found in the castings. The factors which produce the separation of the graphite are briefly outlined.

Making Castings for Hudson River Tunnel (Iron Age, March 8, 1923, vol. 111, pp. 663-667). The foundry operations involved in the production of segmental rings forming the lining for the tunnel under the Hudson River are described and illustrated. The segments are of grey iron, and weigh from $1\frac{1}{2}$ tons to 800 lbs. each. An armour-plate planer has been adapted for milling operations.

E. Schüz, *The Scientific Principles of the Manufacture of Chilled Rolls* (Stahl und Eisen, October 26, November 30, December 28, 1922, vol. 42, pp. 1610-1617, 1773-1781, 1900-1906). The article deals with the technical details of the manufacture of chilled rolls, including rolls for paper mills as well as those for the rolling of metal. A table is given showing the most suitable chemical composition of the metal for casting rolls, and the proportionate weights of rolls and moulds are given. Casting temperatures, contraction, and internal stresses are also considered.

H. E. Diller, *Hubs Cast Entirely in Cores* (Foundry, March 1, 1923, vol. 51, pp. 169-175). A lengthy description is given of the methods adopted in an American foundry for casting iron hubs on to steel wheels. The entire mould is formed of a number of cores, without even the use of a flask. The cores are set on a centre plate of a revolving stand, which holds the rim and spokes. The spokes protrude into the hub and the metal is cast around them.

G. H. Judd, *Scientific Control in Motor Cylinder Founding* (Paper read before the Institution of British Foundrymen: Foundry Trade Journal, December 28, 1922, vol. 26, pp. 528-530). The importance of scientific control in the production of motor cylinders is dealt with.

A. F. Gibbs, *The Manufacture of Locomotive Cylinders using Superheated Steam* (Paper read before the Institution of British Foundrymen: Foundry Trade Journal, October 26, 1922, vol. 26, pp. 336-340). The methods of moulding and casting locomotive cylinders as practised by the Great Eastern Railway at Stratford are outlined.

The mixture used is made up of 25 per cent. of cold-blast pig iron, 25 per cent. hæmatite pig iron, and 50 per cent. scrap.

G. L. Lacher, *Making Radiators under New Conditions* (Iron Age, March 22, 1923, vol. 111, pp. 805-809). The methods of moulding and casting radiators as practised by the Niagara Radiator and Boiler Co., North Tonawanda, N.Y., are described and illustrated.

C. Irresberger, *The Moulding of Baths* (Giesserei Zeitung, February 15, 1923, vol. 20, pp. 75-81). An illustrated description of the method of moulding and casting domestic baths.

P. Dwyer, *How Sanitary Ware is Made* (Foundry, December 1, 1922, vol. 50, pp. 935-941, 997-1002). An illustrated description is given of American practice in moulding and casting domestic baths. The greatest care is required in the production of these castings, since the slightest defect prevents the proper adhesion of the enamel. The methods of applying the enamel are outlined. Up-to-date methods of producing soil-pipes are also described.

P. Dwyer, *Castings for Heat Radiation* (Foundry, January 1, 1923, vol. 51, pp. 1-7). The manufacture of castings for steam and hot water heating purposes, as carried out at the plant of the Gurney Foundry Co., Framingham, Massachusetts, is illustrated and described.

F. A. Melmoth, *Notes on the Development of the Manufacture of Steel Castings* (Paper read before the Institution of British Foundrymen, November 2, 1922; Foundry Trade Journal, November 2, 1922, vol. 26, pp. 355-358). The author describes the various methods and operations in the production of light- and medium-weight steel castings.

J. Kent Smith, *Vanadium in the Steel Foundry* (Foundry Trade Journal, April 12, 1923, vol. 27, pp. 302-303). The influence of vanadium on steel, and its use in the production of steel castings, are described.

Semi-Steel.—F. Wüst and P. Bardenheuer, *Semi-Steel* (Mitteilungen a. d. Kaiser-Wilhelm Institut für Eisenforschung, 1922, vol. 4, pp. 125-144). The constitution, methods of manufacture, and strength properties of high quality, low carbon cast iron, or semi-steel, are described and tabulated. The most suitable composition appears to be: total carbon from 2.50 to 3.00 per cent., silicon from 1.2 to 2.2, manganese 0.7 to 1.2, phosphorus 0.03, sulphur 0.003 per cent. Tensile tests give the following average results: tensile strength 31, and transverse strength, 57 kilogrammes per square millimetre; deflection, 16 millimetres; Brinell hardness 220.

G. Muntz, *Throws Light on Steel Melting* (Foundry, January 15, 1923, vol. 51, pp. 77-79). The melting of steel scrap in the cupola is dealt with. The author's method is to include pig iron in the first charge to maintain fluidity. Charges of scrap may succeed each other continuously as long as the operation of the cupola is continued, and in this case the proportion of pig to scrap is negligible.

Electric Furnace Practice in the Foundry.—L. J. Barton, *Grey Iron Castings from Electric Furnace* (Iron Age, January 25, 1923, vol. 111, pp. 269–273). The experiments and developments in the production of grey iron castings in the electric furnace are described. Acid and basic practice is compared.

L. J. Barton, *Advantages of Basic-Electric Furnace Iron for Castings to Resist Abrasion* (Engineering and Mining Journal Press, April 7, 1923, vol. 115, pp. 628–630). The author outlines the methods of manufacture of white iron in the cupola and synthetic iron in a basic electric furnace. The synthetic iron is much more satisfactory for the production of crusher-jaws, ball-mill liners, roll-shells, and other parts.

G. K. Elliott, *Grey Cast Iron from the Point of View of the Electric Furnace* (Paper read before the American Foundrymen's Association, May 3, 1923; Iron Trade Review, May 24, 1923, vol. 72, pp. 1535–1537). The author outlines the main features of acid and basic electric furnaces, and discusses the general operating details of both the cupola and electric furnace.

V. C. Faulkner, *Notes on Electric Steel Furnace Practice* (Paper read before the Association Technique de Fonderie, March 16, 1923; Iron and Coal Trades Review, March 23, 1923, vol. 106, p. 418). The underlying principles in the design and operation of electric furnaces for the manufacture of steel castings are outlined.

E. G. Stedman, *Electric Furnace Melting Practice* (Transactions of the American Society for Steel Treating, April 1923, vol. 3, pp. 740–749). A general description of plant and equipment for the manufacture of automobile steel in the electric furnace. The advantages of the electric furnace for steel melting are outlined.

L. J. Barton, *West Favours Electrical Methods* (Iron Trade Review, February 8, 1923, vol. 72, pp. 435–437). The author reviews the developments in the production of iron and steel in the electric furnace on the Pacific coast of the United States, and discusses the future possibilities of the industry. At the present time there are about 40 electric furnaces in operation in this region. Particulars are given of costs of labour and material.

Minton, *Production of Light Steel Castings for Ordnance Work* (Paper read before the American Foundrymen's Association, April 30, 1923). The production of links for army tractors is described. The castings are produced in an acid electric furnace. The nature of the heat treatment is given.

Malleable Castings.—H. R. Simonds, *New Type of Malleable Furnace* (Iron Trade Review, November 30, 1922, vol. 71, pp. 1493–1494). Malleable iron furnaces of new design have been recently installed at the plant of the Arcade Malleable Iron Co., Worcester, Mass. The chief feature is the design of the roof, which is constructed in such a way that the hot gases from the fire-box are swept down along the

surface of the bath to produce efficient melting without the use of air blast.

C. C. Hermann, *Cupola Malleable Production* (Foundry, December 1, 1922, vol. 50, pp. 952-955). Cupola practice for the production of malleable cast iron is described. The effects of the constituents of the charge and of the different elements in the metal are discussed, and the method for calculating the charge is given. A higher annealing temperature than that used for air-furnace iron is required for the cupola iron.

A. V. Landschoot, *Application of Fuel Oil to the Malleable Air Furnace* (Paper read before the American Foundrymen's Association, May 2, 1923). The furnace construction and methods of operation are described, and the advantages of using oil fuel in malleable iron furnaces are outlined.

S. J. Felton, *Malleable Iron Cast in Small Quantities* (Paper read before the American Foundrymen's Association, May 2, 1923; Iron Trade Review, May 3, 1923, vol. 72, pp. 1302-1303). The author deals with the use of 500 and 1000 lb. horizontal, barrel-type, non-crucible tilting furnaces using oil as fuel for melting small quantities of malleable iron.

T. W. Atterbury, *Powdered Coal for Malleable* (Foundry, October 15, November 1, 1922, vol. 50, pp. 815-819, 880-884). The author discusses the advantages obtained in the use of powdered coal for melting and annealing malleable cast iron. The general arrangement of furnaces fitted with powdered-coal burning equipment is shown. With hand-firing the ratio of coal to tons of iron melted was 1 to 2.45 tons, and the melting rate 2.75 tons per hour. With powdered coal there was an average of 1 to 4, with a melting rate of 3.8 tons per hour.

W. H. Poole, *Notes on Malleable Iron Production* (Paper read before the Institution of British Foundrymen; Foundry Trade Journal, April 19, 26, 1923, vol. 27, pp. 309-311, 329-331). The production of white heart malleable cast iron is described.

P. Oberhoffer and J. Welter, *Practice in the Production of Malleable Castings* (Stahl und Eisen, January 25, March 1, 1923, vol. 43, pp. 105-110, 301-306). An investigation has been made on the influence of the composition, and in particular that of sulphur and manganese, of the annealing temperature and of the annealing agent on the properties of malleable castings. The results of the impact test show that with increasing sulphur (from 0.014 to 0.370) the notch-toughness falls; that the use of a strongly acting annealing agent such as red hæmatite improves the notch-toughness as compared with the effect of a weakly acting packing material such as scale, the temperature and annealing period being the same in both cases; that annealing at a higher temperature with a packing material of medium strength increases the notch-toughness in spite of a high sulphur content, and that manganese neutralises the effect of sulphur in so

far as that a manganese content of 0·5 to 0·6, with sulphur at about 0·35 per cent. gives a notch-toughness about equal to that of a material with 0·15 per cent. sulphur and practically no manganese. The annealing temperature has a more important effect than the kind of packing material used. After ten hours at 1030° C. the decarburisation is carried as far as after sixty hours at 900° C.

F. H. Hurren, *Some Failures in Malleable Cast Iron* (Foundry Trade Journal, April 12, 1923, vol. 27, pp. 295–298). The author deals with failures caused by defects in metallurgical and manipulative processes. Faulty moulding practice is not considered. Skin defects, draws, collapse of annealing pans, causes of fragility, and the effects of silicon on the annealing properties of malleable cast iron are discussed.

M. M. Marcus, *Malleable Iron Metallurgy* (Foundry, December 15, 1922, vol. 50, pp. 994–995). Modern practice in the production of malleable iron castings is briefly discussed.

T. Levoz, *European View of Malleable* (Transactions of the American Foundrymen's Association, 1922, vol. 30, pp. 420–430). The author discusses the factors governing the production of good malleable cast iron, and describes the Triplex process of manufacture.

F. L. Prentiss, *Handling Malleable Castings in Process* (Iron Age, March 1, 1923, vol. 111, pp. 591–594). The equipment of the plant of the Maumee Malleable Castings Co., Toledo, Ohio, is described and illustrated. A number of labour-saving devices are in operation, and pulverised coal has been adopted for firing the melting furnaces and annealing ovens.

H. R. Simonds, *Treatment of Malleable Castings* (Foundry, September 15, 1922, vol. 50, pp. 733–736). Describes devices for the testing of malleable castings, and for their packing and handling.

Foundry Sands.—J. E. Fletcher, *Some Characteristics of Moulding Sands and their Graphical Representation*. (This Journal, p. 139.)

J. H. Watson, *Some Notes on Moulding Sands* (Paper read before the Institution of British Foundrymen; Foundry Trade Journal, September 14, 1922, vol. 26, pp. 211–216). The properties of moulding sands are discussed. The essential properties of sand for the production of good castings are refractoriness, venting qualities, strength of bond, and size of grain.

S. H. Cleland, *The Preparation of Steel Foundry Sands* (Transactions of the American Foundrymen's Association, 1922, vol. 30, pp. 826–845).

H. W. Dieter, *The Application of the Microscope and the Camera to the Study of Steel Moulding Sands* (Paper read before the American Foundrymen's Association, April 30, 1923).

R. J. Doty, *A Study of the Change in Grain Size of Silica Sand through Constant Addition of Clay* (Transactions of the American Foundrymen's Association, 1922, vol. 30, pp. 782–795).

Simple Test for Sand (Foundry, January 1, 1923, vol. 51, pp. 34-35). The method devised by E. W. Smith for separating sand from bonding material is given. A 10 or 12 ounce bottle is a quarter filled with sand; the remainder of the bottle is filled with water. The bottle is held on a vibrator plate and vibrated until the heavy grains are all down. It is then allowed to stand until the water is clear. The bond and silica will be found divided by a distinct line. The percentage of either can be measured with a rule.

E. W. Smith, *New Method of Testing Foundry Sands* (Paper read before the Chicago Foundrymen's Club, December 9, 1922: Iron Age, December 28, 1922, vol. 110, pp. 1725-1726). By means of the test described, the bond and silica are separated by vibratory precipitation, and the ferric and aluminium oxides are indicated by colour. The fineness of the sand may be ascertained by the eye with sufficient accuracy to determine the class of work to which it is best suited.

W. West, *Some Tests for Foundry Sands and their Practical Application* (Paper read before the Institution of British Foundrymen: Foundry Trade Journal, December 14, 1922, vol. 26, pp. 495-498).

H. Ries and C. M. Nevin, *The Cohesiveness Test of Foundry Sands* (Paper read before the American Foundrymen's Association, May 1, 1923). The authors give the results of an investigation on the bonding strength of moulding sands. The percentage of water in the sand is shown to be an important factor in bond strength, and in some sands a variation of 1 per cent. total moisture content causes a great difference in cohesiveness.

O. Smalley, *Moulding Sands* (Foundry Trade Journal, May 31, 1923, vol. 27, pp. 435-438). The properties and testing of moulding sands are dealt with.

E. J. Davis, *The Testing of Moulding Sands* (Metal Industry, September 8 and 15, 1922, vol. 21, pp. 219-221, 243-247). The methods of laboratory testing of moulding sands are described, with notes on their chemical, mechanical, and mineral analysis. The requisite properties of moulding sands are also discussed.

C. S. Koch, *Core Mixtures for Light Steel Castings* (Paper read before the American Foundrymen's Association, May 3, 1923). It is shown that it is unnecessary to use linseed oil in all core mixtures. For many classes of castings equally satisfactory results could be obtained by the use of corn flour binders and pitch, or paper mill by-product binders. The methods of ramming, drying, and testing of cores are dealt with.

Moulding and Pattern Making.—J. D. Nicholson, *Dry Sand Moulding for Small Work* (Paper read before the Institution of British Foundrymen: Foundry Trade Journal, December 14, 1922, vol. 26, pp. 485-488). The moulding of small intricate castings in dry sand is discussed.

H. R. Simonds, *Moulding Large Card Cylinders* (Foundry, February 1, 1923, vol. 51, pp. 87-92). An illustrated account of the

methods adopted by an American foundry for the production of large cylindrical castings used in the textile industry.

W. H. Parry, *Three-Part Moulds Advocated* (Paper read before the American Foundrymen's Association: Foundry, October 1, 1922, pp. 806-807). The advantages claimed for the three-part mould for castings are an increased number of patterns in the flask, better arrangement of gates and runners, and time saved in preparing the mould.

R. Moldenke, *New Long-Life Mould Development* (Paper read before the American Foundrymen's Association: Iron Age, May 3, 1923, vol. 111, pp. 1251-1254). The author describes the use of cast iron moulds, faced with a refractory material, in an American foundry. Some of the moulds have had 10,000 castings made in them. The iron backing of the mould is comparatively thin. The refractory material forming the mould surface can be of any of the usual substances, such as magnesia, bauxite, fire-clay, or kaolin. A binder is used to bind the refractory to the iron.

T. F. Hardyman, *Machine Moulding Methods* (Paper read before the Institution of Production Engineers, February 23, 1923: Practical Engineer, March 8, 1923, vol. 67, pp. 129-131). The use of moulding machines for the production of various castings is dealt with.

H. M. Lane, *Quantity Production of Automobile Cores* (Iron Age, March 15, 1923, vol. 111, pp. 745-751). An illustrated description of the methods of making cores for automobile castings practised by a large American foundry.

F. C. Edwards, *A Few Points on Pattern-Making* (Paper read before the Institution of British Foundrymen: Foundry Trade Journal, February 8, 1923, vol. 27, pp. 113-116).

J. Horner, *Construction of Core-Boxes* (Foundry, February 15, March 1, vol. 51, pp. 157-160, 188-192). An illustrated description of the methods for the construction of core-boxes of various patterns.

Foundry Equipment.—*Some Modern British Foundries* (Iron and Coal Trades Review, October 6, 1922, vol. 105, pp. 487-488). The equipment of the foundries of the following firms is described: Ealing Park Foundry, London; Britannia Iron Works, Bedford; Braintree Castings Co., Braintree; and Wolseley Motors, Ltd.

Works of Messrs. Fraser & Chalmers (Foundry Trade Journal, November 9, 1922, vol. 26, pp. 377-382). Illustrated particulars are given of the lay-out of the foundry of Fraser & Chalmers, Erith, Kent.

B. Schapiro, *Modern Foundries of Central Europe* (Foundry, November 15, December 1, 1922, vol. 50, pp. 900-905, 908, 946-951). An illustrated account is given of the lay-out, equipment, and practice of typical modern Austrian foundries.

The Henri-Paul Foundry of Messrs. Schneider & Cie. (Science et Industrie: Foundry Trade Journal, January 18, 1923, vol. 27, pp. 48-

56). An illustrated description of the equipment and methods of operating the above foundry for the production of heavy castings.

New Steel Foundry (Iron Age, February 22, 1923, vol. 111, pp. 543-544). The lay-out and equipment of the new foundry of the Crucible Steel Castings Co., Cleveland, U.S.A., are described and illustrated.

H. M. Lane, *Foundry Lay-Out and Material Handling* (Paper read before the National Founders' Association: Iron Age, April 12, 26, 1923, vol. 111, pp. 1037-1040, 1173-1176). A general description of the lay-out of the foundry and methods of handling material at the plant of the Wilson Foundry and Machine Co., Pontiac, Michigan.

G. F. Charnock, *Mechanical Appliances in the Foundry* (Paper read before the Institution of British Foundrymen: Foundry Trade Journal, March 1, 1923, vol. 27, pp. 171-177). An illustrated description is given of types of mechanical appliances for charging cupolas and sand handling.

P. Dwyer, *Mechanical Handling Aids Speed Production of Motor Castings in Cleveland Foundry* (Iron Trade Review, April 26, 1923, vol. 72, pp. 1225-1231). An illustrated description is given of the extended use of mechanical handling equipment in an American foundry.

F. L. Prentiss, *Eliminating Skilled Foundry Labour* (Iron Age, April 5, 1923, vol. 111, pp. 949-954). An illustrated description of the equipment and methods adopted at the plant of the Ferro Machine and Foundry Co., Cleveland, U.S.A. By the use of special machines and conveyors 500 cylinder castings are produced daily, employing only seventeen semi-skilled men.

H. E. Diller, *Technical Men Direct Foundry* (Foundry, October 1, 1922, vol. 50, pp. 775-782). An illustrated description is given of the equipment and methods for the production of automobile castings in an up-to-date American foundry.

PRODUCTION OF STEEL.

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I.—PROCESSES OF STEEL PRODUCTION.

Crucible Steel.—T. H. Nelson, *Comparison of American and English Methods of Producing High Grade Crucible Steel* (Transactions of the American Society for Steel Treating, December 1922, vol. 3, pp. 279–298). About 80 per cent. of the crucible tool steel made in Sheffield is produced in coke-hole furnaces using clay pots. In America the gas-fired furnace is used, and the pots are of plumbago or graphite, a mixture of Ceylon graphite and fire-clay. It is possible to obtain anything from five to ten heats with a plumbago pot, as compared with a limit of three with the clay pot used in England. The plumbago pot, offering as it does such an increased life, has its disadvantages. The carbon in the pot is absorbed by the steel in its liquid condition, and it is not possible to forecast with any degree of certainty to what extent the carbon absorption will take place. With the Sheffield clay pot a great degree of uniformity in the finished steel is obtained. By the introduction of ladle teeming in American practice a degree of uniformity is established quite comparable with the English standard. In England the production is considerably lower, 4500 pounds in three heats as compared with 18,000 pounds in six heats in American practice. The nature of the mixtures employed is given, together with typical analyses of English high-speed steel, magnet steel, and special alloys steels.

The Bessemer Process.—F. Wüst, *The Behaviour of Nitrogen in the Basic Bessemer Process* (Mitteilungen a.d. Kaiser-Wilhelm Institut für Eisenforschung, 1922, vol. 4, pp. 95–104). This research is in continuation of one previously carried out by Wüst and Duhr. (See *Journal of the Iron and Steel Institute*, 1922, No. I. p. 650, Abstract.) The variation in the amount of nitrogen in samples of basic steel from different works was difficult to account for, and a further investigation has now been made to try and clear the matter up. Samples were obtained from ten different works, and were grouped as follows:—Group 1: Four samples were taken from each charge, the times at

which they were taken in the course of the blow being the same in each case, namely (1) on charging the pig iron into the converter, (2) before deoxidation and slagging off, (3) after deoxidation and on teeming into the ladle, (4) from the metal remaining in the ladle after teeming the last ingot. In the taking of the above series of samples the deoxidiser was added solid in the converter. In some instances the deoxidiser was added in molten condition in the ladle, and No. 3 sample was then taken after teeming the first ingot, the others all being taken as before. The analysis of the samples was made according to a method described in the previous article, and the results summarised show that the nature of the raw materials has no particular influence on the nitrogen content of basic Bessemer steel; that the quantity of nitrogen taken up increases with the temperature of the bath; that in all probability a high blast-pressure promotes the taking up of nitrogen; and that the nitrogen content can be lowered by cooling the bath with scrap additions and by the avoidance of too high a blast-pressure.

The Dedication of a Bronze Tablet to the Memory of William Kelly (Transactions of the American Society for Steel Treating, November 1922, vol. 3, pp. 162-174). On October 5, 1922, before a large delegation of members of the American Society for Steel Treating, a tablet was unveiled to perpetuate the memory of William Kelly, who is credited with being the first and the original producer of steel in the United States by means of a pneumatic converter. The tablet is placed on the wall of the public library in Wyandotte, Michigan, which was formerly the site of the Wyandotte Iron Works, where, in 1864, Kelly's first tilting converter operated. During the ceremony addresses were made by R. W. Hunt and W. C. Kelly, giving the early history of the process.

The Open-Hearth Process.—J. T. Wright, *The Basic Open-Hearth Process* (Proceedings of the Cleveland Institution of Engineers, Session 1922-1923, No. 4, pp. 121-151). The author discusses some of the points bearing upon the general efficiency of the basic open-hearth furnace under the following headings: Manufacture of producer-gas, use of waste gases from blast-furnace gas-fired boilers, various types of gases used in the open-hearth, velocity of flame, effect of excess air upon the flame temperature, the use of oxygen or oxygenated air for burning producer-gas, conservation of heat in the regenerators, the slag, and condition of metal.

C. C. de Coussergues, *Influence of Temperature in the Manufacture of Steel* (Liège Congress, June 1922: Revue de Métallurgie, Mémoires, November 1922, vol. 19, pp. 639-644). The most important factor in steel manufacture is to obtain the highest possible temperature, and therefore it is necessary to have appliances which can heat the bath up rapidly and take it to the highest required temperature as quickly as possible. In spite of the endeavours of the last twenty years, the

fact remains that large open-hearth furnaces frequently only produce nine charges per week. On the other hand, the manufacture of special steel, particularly in America, is carried out in the electric furnace at temperatures which are distinctly lower than those reached in open-hearth furnaces. Hence it would appear that, notwithstanding the progress made in heating appliances, it is not a generally recognised fact that a very high temperature in the steel bath represents any real progress in practice. Indeed, the question of temperature is complicated by the fact that the various reactions in the furnace take place at different temperatures. The selective action of oxygen leads to very different reactions at some temperatures, and these require careful investigation before the best practice can be obtained. The first stage, which involves the melting down of the charge, is followed by a more important stage, where the various reactions occur, and where the relation between the bath of metal and the supernatant slag become exceedingly important. For this phase it is necessary, so to speak, to damp down the temperature somewhat at times. The average temperature desirable would appear to be 1600°C . Various reactions are considered in detail, and the effect of each addition is similarly investigated. The general conclusion arrived at is that in the quick driving of a basic-lined furnace there are three periods which are important, and not two as has hitherto been thought. The earlier view attached greater importance to the two successive phases, dephosphorisation and deoxidation. The actual periods would seem to be :

1. The period of the formation of the slag and of oxidation. During this period heating is carried in the Bessemer process to the highest possible extent, and in the open-hearth furnace, so in the electric furnace, to the extent only of melting a portion of the charge, and of the formation of the slag.

2. The period of deoxidation by phosphorus, while the remainder of the charge is added, and, if necessary, a certain amount of reoxidation allowed.

3. The removal of the excess carbon and the completion of the deoxidation (by means, in the electric furnace, of the slag).

H. D. Hibbard, *Calorific Value of Steel-Making Elements* (Iron Age, January 11, 18, February 1, 1923, vol. 111, pp. 143-144, 211-213, 347-349). The chemistry of fusion or the rôle of the various elements employed in the fusion processes in iron and steel manufacture are discussed under the following headings : Calorific power of the elements ; the rôle of oxygen and carbon in the blast-furnace and open-hearth furnace ; rôle of silicon in Bessemer converter and open-hearth furnace ; the proper use of aluminium ; the use of magnesium as a deoxidiser ; the behaviour of phosphorus, manganese, and other metals in the steel processes, and the peculiarities of sulphur.

P. Oberhoffer and F. Koerber, *The Behaviour of Manganese in the Basic Open-Hearth Process* (Stahl und Eisen, March 8, 1923, vol. 43,

pp. 329-334). The influence of the basicity of the slag, of the proportion and form of the manganese contained in the charge, of the ore additions, and of the carbon content of the bath is considered in relation to the working of the charge in the basic open-hearth furnace. The conditions under which manganese of the slag is taken up by the bath are also dealt with.

W. H. Keen, *Aluminium in Steel* (Iron Age, December 14, 1922, vol. 110, pp. 1574). The author discusses the advantages of the addition of aluminium to steel and indicates how the additions should be made.

F. M. Becket, *Some Effects of Zirconium in Steel* (Paper read before the American Electrochemical Society: Iron Age, May 10, 1923, vol. 111, pp. 1321-1323). Zirconium has a greater affinity for oxygen than has silicon and, due to this fact, increased recoveries of silicon in the finished steel are obtained by the use of zirconium-silicon alloys. The rate of the reducing action of zirconium on the impurities present in molten steel is not only more rapid than that of silicon, but zirconium is the more efficacious in removing final traces of oxygen and nitrogen. No indication of the occurrence of inclusions of zirconium oxide were observed in the course of the investigation. All the evidence points to the conclusion that oxidised zirconium forms with silica and oxide of manganese a fusible slag which quickly rises to the surface of the ladle. Minute, yellow crystals of zirconium nitride are generally observed in steels treated with zirconium in excess of approximately 0.10 per cent. These crystals do not exert a harmful effect on the steel. When zirconium is added to steel in excess of approximately 0.15 per cent., this element assumes a new rôle by chemically combining with sulphur to form an acid insoluble compound not detected by means of the ordinary evolution method of analysis, and under any given set of operating conditions a linear relation exists between the percentage of sulphur thus fixed and the amount by which the added zirconium exceeds 0.15 per cent. Under favourable conditions the zirconium-sulphur compound may be actually eliminated from the steel by fairly heavy additions of zirconium-silicon alloy. In order to obtain the full beneficial effect upon hot-rolling properties, the zirconium alloy need be added only in amount sufficient to eliminate the iron sulphide constituent responsible for red shortness. Ingots containing 0.185 to 0.2 per cent. of sulphur and 0.15 per cent. of manganese have been rolled to sheets free from cracks and seams when the steel had been treated with 0.22 per cent. of zirconium.

J. M. Quinn, *A Short Method for Calculating Ferro-Alloy Additions* (Blast-Furnace and Steel Plant, April, May, 1923, vol. 11, pp. 232-238, 279-282). The author presents a comprehensive system of tables and proportions for the use of practical steel makers in calculating ferro-alloy additions to charges of manganese steel, high-speed steel, and ordinary steel for castings.

B. B. Russell, jun., *Slide Rule for Open-Hearth Calculations* (Iron

Age, January 18, 1923, vol. 111, pp. 224-225). A description is given of a new slide rule designed for making calculations of cost of various open-hearth charges. A chart is also given for making similar computations.

S. V. Williams, *Control of Sulphur in the Basic Open-Hearth Process* (Blast-Furnace and Steel Plant, January, 1923, vol. 11, pp. 51-54). The article deals generally with the problems of minimising the entry of sulphur into the open-hearth, by control of the pig iron, scrap, fluxes and fuel, and of eliminating the sulphur from the bath by the use of a limey slag, ferro-manganese, calcium chloride, and calcium carbide.

A. Barberot, *The Progress Achieved in Open-Hearth Furnaces* (Revue de Métallurgie, Mémoires, January-February, 1923, vol. 20, pp. 1-26, 95-111). A summary of modern progress in open-hearth steel practice commencing with an historical account of the invention of the process and tracing its development since. The principles involved, and the plant are described, the latter being fully illustrated. The sequence of the various operations and the chemical reactions upon which the working of the charges are based are discussed as well as the variants of the ordinary process, such as the Duplex, the Bertrand Thiel, and the Talbot processes.

A. Jung, *The Working of Liquid Basic Pig in a Stationary Open-Hearth Furnace with only one Slag* (Report of the Steelworks Committee of the Verein deutscher Eisenhüttenleute, No. 69). Details are given of the working of two heats using liquid Ilseeder pig iron.

T. P. Colclough, *The Constitution of Basic Slags: Its Relation to Furnace Reactions*. (This Journal, p. 267.)

J. H. Whiteley, *The Dephosphorisation of Iron in the Basic Furnace* (Proceedings of the Cleveland Institution of Engineers, Session 1922-23, No. 2, pp. 36-65). It is shown that the phosphate content of the slag and the phosphorus content of the metal may be increased or diminished simply by changing the concentration of silica. The number of molecules of bases available for each molecule of silica in a slag, after deducting the amount required to form $3 \text{ROP}_2\text{O}_5$, is taken as an index of the basicity. It is shown that, when equilibrium is established, the ratio of the percentages of phosphorus in slag and metal, termed the distribution factor, is a linear function of the basicity index. Since, in the absence of appreciable amounts of other acids such as Al_2O_3 , the basicity index depends upon the silica content, the quantity of this substance present is the chief factor in dephosphorisation. The relation existing between the basicity index and the distribution factor has not been found to be affected by variations in slag volume such as obtain in ordinary practice. It has been found possible to determine the phosphorus content of the steel, to within fairly narrow limits, from the analysis of the finishing slag. The disturbing effect of iron oxide in the bath on the equilibrium is also considered, and it is shown that in most cases 6 to 7 per cent. of iron in the tapping slag is sufficient to prevent rephosphorisation occurring to any

important extent, provided that the required basicity index is reached by the use of other bases.

G. Donner, *Experiments in the Heating of Open-Hearth Furnaces with Pressure Gas* (Stahl und Eisen, April 26, 1923, vol. 43, pp. 558-563). The experimental 3-ton furnace had no gas uptake, the gas being admitted through a burner direct into the air-port well above the bath, and the flame directed downwards upon the surface of the metal. The best results were accomplished with cold gas, of such a composition that its temperature of combustion was 1800° to 2000° C., and admitted at a pressure of about 5 atmospheres, the air being heated to about 1100° C. The burner should be of a type that will cause a thorough mixing of the gas with the hot air. With a mixture of water-gas and producer-gas having a calorific value of 2000 calories, a 3-ton charge under these conditions was melted and finished in about two hours.

A. D. Williams, *Heat Generation in Open-Hearth Practice* (Paper read before the American Foundrymen's Association, April 30, 1923). The author discusses the relative merits of the various kinds of fuel used in open-hearth practice and some of the principles governing their application.

E. H. Schulz, *The Operation of the Tilting Furnaces of the Dortmunder Union, with Special Reference to the Problem of Heating* (Report of the Steelworks Committee of the Verein deutscher Eisenhüttenleute, No. 64). The furnaces are fired with a mixture of coke-oven gas and blast-furnace gas, and the heat-balance has been worked out, using gas of low-heating value and a richer gas. The mixed gases undergo changes owing to heating in the regenerator chambers. Some trials with coal-dust firing have also been carried out.

O. Schweitzer, *Method of Working in the Open-Hearths of the Hoesch Iron and Steel Works, with Special Reference to the Hoesch Process and the Firing of the Furnace with Coke-Oven Gas* (Report of the Steelworks Committee of the Verein deutscher Eisenhüttenleute, No. 63). A description of the Hoesch process and the method of working. The advantages of firing with coke-oven gas are discussed.

W. Trinks, *Heat Balances of Blast-Furnace and Steel Plants* (Blast-Furnace and Steel Plant, September, 1922, vol. 10, pp. 451-456). A series of charts are given showing the heat-balances of an uneconomical steel plant, an average steel plant, an economical steel plant, and an ideally operated one, the calculations being based in each instance on one pound of finished steel.

E. L. Shaner, *Steelmakers Strive for Higher Open-Hearth Efficiency* (Iron Trade Review, January 4, 1923, vol. 72, pp. 60-61). A brief outline is given of the developments that have taken place during the past year in open-hearth practice and design.

New Type of Open-Hearth Furnace (Iron Age, December 28, 1922, vol. 110, pp. 1677-1679). An illustrated description is given of the Loftus furnace which has been in operation in the United States for several months. The furnace involves a new method of applying

the blow-torch principle. The gas is discharged from a restricted nozzle into a mixing chamber, inducing the supply of air necessary for combustion. A booster supply of regenerated air is withdrawn from the regenerative chamber passed through a special blower driven by a variable speed motor, and introduced into the centre of the stream of gas in the direction of its flow through the furnace. The pressure and volume of this booster supply of regenerated air may be governed by the control of the variable speed motor, in this way giving the operator control over the flame. The old type of gas uptake with its abrupt turn has been replaced by a stream line elbow readily capable of adjustment in all directions, so that the path of the gases may be suitably altered after the furnace has been put into operation. The Loftus furnace has been in operation in a plant and has been able to produce an average of approximately 30 per cent. more steel than other furnaces with a similar percentage in saving of fuel per ton of ingots.

E. C. Cook, *Improvements in the Open-Hearth* (Blast-Furnace and Steel Plant, January 1923, vol. 11, pp. 61-64). The Loftus variable-pressure method of firing open-hearth furnaces is further illustrated and described. The furnace is fitted with the Naismith mechanical neutral joint, which consists of a steel-plate construction with water cooling, forming a complete course in the furnace wall at the slag zone.

G. Neumann, *Improvements in the Construction of American Open-Hearth Furnaces* (Stahl und Eisen, November 2, 1922, vol. 42, pp. 1641-1650). The article describes some open-hearth furnaces of modern design in America. In particular sectional drawings are shown of a 25-ton stationary furnace, with water-cooled ports, walls, and doors. The walls of the regenerators and flues are air-cooled by means of pipes built into the brickwork. The furnace is fired with producer-gas, with an arrangement to enable coke-oven gas to be mixed with the producer gas. Coal-tar fuel burners are also fitted in the gas port, and the furnace can be fired with tar fuel alone or with tar as an auxiliary fuel. The furnace crown is of the Orth type, consisting of arches spaced about 18 inches apart, and built of bricks about 16 inches deep, the vaulting in between being 12 inches deep. The arches thus form ribs standing out about 4 inches above the vaulting on the outside. A tilting open-hearth furnace of 200 tons capacity is next illustrated and described, all the drawings being executed with great clearness.

E. Blau, *Modern Types of Siemens-Martin Furnaces* (Giesserei Zeitung, October 10, 1922, vol. 19, pp. 585-590). The article gives a general description, with illustrations, of open-hearth furnaces of modern design, with special reference to the construction of regenerators, uptakes, gas and air ports.

E. Diepschlag, *Open-Hearth Furnace Ports of New Design* (Report of the Steelworks Committee of the Verein deutscher Eisenhüttenleute,

No. 67). The conditions for good combustion as obtained in furnaces of new construction are discussed.

H. Hellan, *A Study of Valves for Furnaces* (Blast-Furnace and Steel Plant, September 1922, vol. 10, pp. 473-477). The construction of various types of valve in use for regenerative furnaces is discussed, and a valve of new design is described, which embodies certain improvements with a view to the prevention of impact on the seats when closing, the provision of an abundant water supply for the seal and for cooling, the simplification of the flue design, and the prevention of the collection of dust in flues adjacent to the valves.

Canadian Open-Hearth Practice (Iron and Coal Trades Review, April 20, 1923, vol. 106, pp. 555-556). Particulars of design and working results of the McKune furnace in operation at the Hamilton Works of the Steel Company of Canada are given.

Steelworks Equipment.—*Developments at the Works of the North-Eastern Steel Co., Middlesbrough* (Iron and Coal Trades Review, November 24, 1923, vol. 105, pp. 761-764). An illustrated description is given of the new equipment of these works, where the basic Bessemer process has been abandoned in favour of the open-hearth process. The equipment includes a 400-ton mixer and two furnaces of 180 tons capacity. Another furnace is in course of erection, and provision is made for a fourth furnace. Two nests of gas-fired soaking pits and two Stein and Atkinson continuous-push furnaces heat 4000 tons of ingots per week for the rail mill. A new slag-grinding plant has also been installed.

The Mossend Steelworks and Rolling-Mills (Engineering, October 13, 20, November 3, 17, 24, 1922, vol. 114, pp. 447-448, 484, 543-545, 603-606, 641-643). A description of these works of Messrs. William Beardmore and Co., Ltd., is published, with plans and illustrations. The plant consists of sixteen 50-ton open-hearth furnaces, with rolling-mills for the production of sections used for shipbuilding and structural work, and a rail mill.

Krupps Build New Open-Hearths (Iron Trade Review, March 1, 1923, vol. 72, pp. 661-663). Illustrated particulars are given of the new open-hearth plant of Fried. Krupp A.G., at Essen. The four furnaces are of the tilting type, of 80 tons capacity. The cold pig and scrap process is used at present, but provision is made for the molten process in the future.

Making Steel in Java (Iron Age, March 22, 1923, vol. 111, p. 820). A small basic open-hearth furnace has been put into operation at Batavia, Java, for the production of castings for the railroad. It is designed to use oil as fuel. The capacity of the furnace is 3 tons, and the charge is made up of 50 to 60 per cent. of steel scrap and the remainder cast iron scrap. Ore is obtained from Borneo.

H. Fromm, *Cost of Transport and Handling Material in Open-Hearth Steelworks* (Stahl und Eisen, November 23, December 7, 1922,

vol. 42, pp. 1737-1742, 1809-1815). The first portion of the article consists of a bibliography of German literature describing and illustrating installations and apparatus for transporting and handling coal, ash, material to form additions in the furnace, the raw materials forming the charge, the liquid metal, ingots, ingot moulds, slag, &c. The author then works out, for a typical steelworks, the proportion of the total cost of production to be allocated as representing the cost of handling and transport within the works.

H. T. Morris, *Waste in the Steel Industry* (Paper read before the American Iron and Steel Institute, May 25, 1923, 15 pp.).

Electric Steel Furnace Practice.—J. M. Quinn, *Acid Electric Steel Furnace Operation* (Iron Age, April 26, 1923, vol. 111, pp. 1177-1179). The controlling factor in the operation of the acid process seems to be the quantity of iron oxide present at the time the heat is melted, irrespective of whether this oxide is introduced with the scrap as rust or whether it results from oxidation due to air leaks in the furnace, or from the addition of iron ore. The reduction of iron oxide from an acid slag and the method of charging the scrap are dealt with.

W. Scott, *Electric Furnace Operation* (Iron and Coal Trades Review, October 13, 1922, vol. 105, p. 538). The principles involved in the successful operation of electric furnaces are briefly outlined.

F. Hodson, *Molten Ferro-manganese* (Iron Age, March 8, 1923, vol. 111, p. 677). The author discusses the advantages of the use of electrically melted ferro-manganese in steel-making. The effect of hot ferro-manganese on steel is very much more pronounced than when the alloy is added cold. It has been found that the actual amount of alloy used can be reduced 30 to 40 per cent. in favour of the molten process. It is desirable to use an electric furnace with a large open bath rather than a restricted channel as in the induction furnace, and also one in which there is a circulation from the bottom of the furnace.

E. F. Cone, *Electric Steel Industry After Ten Years* (Iron Age, January 4, 1923, vol. 3, pp. 80-83). Particulars are given of the number and types of electric furnaces in operation in the United States and Canada. Ten years ago there were nineteen furnaces in the United States and three in Canada, while on January 1, 1923, there were 406 furnaces in the United States and 50 in Canada.

F. Hodson, *Change Electric Furnace Design* (Paper read before the American Institute of Electrical Engineers, April 1923: Iron Trade Review, May 17, 1923, vol. 72, pp. 1462-1464). An illustrated description is given of the design of the 60-80 ton Greaves-Etchells furnace under construction at the plant of the Ford Motor Company, Detroit.

E. T. Moore, *Recent Electric Furnace Developments* (Blast-Furnace and Steel Plant, February 1923, vol. 11, pp. 153-158). The article describes recent improvements in the design and equipment of the

Heroult furnace, the Greaves-Etchell furnace, and the Moore Lectro-melt furnace.

* J. M. Quinn, *Lining Acid Electric Furnaces* (Iron Age, April 19, 1923, vol. 111, pp. 1101-1102). The materials used and the methods of lining are discussed.

Fluorspar.—G. H. Jones, *Fluorspar and its Uses* (Paper read before the American Iron and Steel Institute, October 27, 1922). The geology of the fluorspar region in the State of Illinois is described. In this district one notable fissure vein occurs, known as the Rosiclare vein, which with several parallel veins formed at the same time has produced nearly all the fluorspar mined in Illinois. Statistics of production show that the output of fluorspar in the United States rose from 4000 tons in 1883 to 186,700 tons in 1920. In 1921 the shipments dropped to 35,000 tons, due to large stocks and depression in the steel business. The average prices during the three years 1918-19-20 are stated. Of the total production 80 to 85 per cent. is used in the basic open-hearth steel furnace and in the electric furnace.

Use of Basic Slag.—D. N. McArthur, *The Constitution and Manurial Value of Low Grade Basic Slag* (Journal of the Society of Chemical Industry, May 18, 1923, vol. 42, pp. 213-216-T). The investigation was undertaken to ascertain the relation between the constitution of a slag and its manurial value. The slag was obtained from an ordinary open-hearth charge of basic pig iron and steel scrap, while fluorspar containing 70 per cent. calcium fluoride was added to the bath to the amount of 3 per cent. of the weight of the slag. The slag was ground to different degrees of fineness for the trials, and it contained 6.48 per cent. phosphoric acid, 12.2 per cent. silica, and 38.23 per cent. lime. The experiments made on farm land showed that open-hearth fluorspar slags of low phosphate content have a distinct fertilising value in their lime content, and could replace ground limestone in agricultural practice. The finely ground material gives distinctly better results than the coarsely ground.

II.—CASTING AND TREATMENT OF INGOTS.

Steel Ingot Moulds.—F. Schivetz, *The Use of Steel Ingot Moulds in Place of Cast Iron Moulds* (Stahl und Eisen, December 28, 1922, vol. 42, pp. 1897-1900). Owing to the deterioration of the quality of cast iron in Germany during the war the life of the cast iron ingot moulds in a steelworks was so greatly reduced that it was decided to make use of ingot moulds of steel. The life of the cast iron moulds before the war had averaged 150 teemings, but it had fallen in 1917 to 60 or

70 teemings. Steel moulds of various compositions were tried, and it was found that with material containing carbon from 0.33 to 0.38, manganese 0.44 to 0.50, phosphorus 0.07 to 0.08, silicon 0.10 to 0.24, and sulphur 0.04 to 0.05 per cent. the moulds, if carefully handled, had a life ranging from about 200 to 300 teemings. Burnt magnesite was the material used for moulding in casting the steel moulds.

Sound Steel.—T. Swinden, *Notes on the Production of Sound Steel* (Proceedings of the Staffordshire Iron and Steel Institute, 1922–23, vol. 37, pp. 80–102). The study of gases in connection with steel-making is a difficult one, and the results obtained by different workers are not entirely consistent. The author suggests that a complete explanation of blow-hole unsoundness must take into account the presence of hydrogen. The generally accepted hypothesis that blow-holes are produced by carbon monoxide or carbon dioxide, and are governed by the content of dissolved FeO in the steel, ignores hydrogen. There is evidence to show that the action of manganese, silicon, and aluminium whilst removing FeO and consequently carbon-monoxide as a source of blow-holes, increases the power of the steel to retain hydrogen in a state of absorption.

H. W. Gillett, *Application of Colloid Chemistry to Production of Clean Steel* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). It is pointed out that a large proportion of failures of steel parts in service are often due to inclusions. Dirt or inclusions are present in the molten metal as an emulsion or suspension of colloidal nature. Present methods tend to destroy such colloidal suspension, but they produce only relatively clean steel. Other methods of destroying such suspensions are known to the colloid chemist, but too little is known of the fundamental properties of colloids in molten metals to allow direct application of these methods.

O. A. Knight, *Defects in Steel Ingots and Castings* (Forging and Heat-Treating, February 1923, vol. 9, pp. 98–102). A general discussion of the defects commonly found in steel ingots and of the practice and procedure to be adopted to eliminate or diminish them.

Segregation.—E. G. Mahin and H. W. Botts, *Non-Metallic Inclusions and Ferrite Segregation in Steel* (Chemical and Metallurgical Engineering, November 15, 1922, vol. 27, pp. 980–985). It is believed that the influence of non-metallic inclusions upon ferrite segregation in slowly cooled hypoeutectoid steel is principally due to the fact that the inclusions are centres of contamination for the steel mass rather than to any connection between dissolved gases and the state of oxidation of the inclusion. The development of coloured halos surrounding many of the inclusions of a polished steel or iron section, and of similar rings when such a section is treated with antimony tartrate solution, indicates the correctness of this assumption. Howe's hypothesis with

respect to ferrite genesis is regarded as being correct, except for steels during their first cooling from the liquid state.

T. H. Turner, *Ingot-Corner Segregation in a Nickel-Chrome Steel* (Paper read before the Staffordshire Iron and Steel Institute : Iron and Coal Trades Review, November 24, 1922, vol. 105, pp. 774). The author describes his experiences encountered in the examination of forgings of nickel-chrome steel. Such steels have failed at parts most highly stressed. A hollow cylindrical bell, 3 feet in diameter, 1 foot high, and 3 inches thick, bore one or two faint markings on the machined surface. The lines were regular, and extended the whole length of the cylinder. Further investigation showed that planes of segregation were to be found at places corresponding to the positions of all the eight corners of the original ingot mould.

Photomicrographs which were taken from the sections prepared showed that between the segregated areas the steel was a normal fine-grained and slag-free sample, and that the segregation consisted largely of manganese sulphide. The production of such planes of segregation could be avoided by the use of new mould shapes, and by better regulated pouring rates and temperatures.

O. Bauer, *Segregation of Phosphorus in Mild Steel* (Mitteilungen aus dem Materialprüfungsamt, 1922, vol. 40, pp. 71-88). The phenomenon of segregation in mild steel ingots is generally discussed. Enrichment in sulphur may be detected microscopically or by means of silver bromide paper, and phosphorus-rich mixed crystals are detected by darkening on treatment with copper ammonium chloride. Examples with photographs and analyses are given of segregation phenomena in rails, angles, and tubes, and the effect of phosphorus is shown by a number of bending tests on sheets and by impact tests.

Centrifugal Casting of Steel.—W. McConway, *The Centrifugal Casting of Steel* (Paper read before the American Foundrymen's Association, April 30, 1923). The McConway centrifugal casting process is described.

G. F. Tegan, *Special Products made Centrifugally* (Iron Age, February 1, 1923, vol. 111, pp. 337-338). The production of steel discs for tires, wheels, and other shapes by the McConway centrifugal process is described and illustrated. (See also Journal, 1922, No. II. pp. 249-251.)

L. Cammen, *Casting Steel Ingots Centrifugally* (Iron Age, December 7, 1922, vol. 110, pp. 1494-1496). A review is given of some early attempts to cast steel ingots centrifugally, and the Cammen process is described. In this process a horizontal bottle-neck mould is used, and ingots can be produced at 0.367 dollars per ton, not including overhead charges.

FORGING AND ROLLING-MILL PRACTICE.

Forging Practice.—H. Johnson, *Forging Furnace Construction* (Forging and Heat-Treating, October 1922, vol. 8, pp. 477-479). The proper design of oil-fired furnaces is outlined. The essential considerations are: the necessity of sufficient combustion space in forging furnace construction, the efficiency attained by producing the reverberatory flame in the forging furnace, the necessity of maintaining the fuel oil at a given temperature when fired, properly atomising the oil, and the necessity of free air to complete combustion.

New Oil-Fired Forge Heating Furnaces (Forging and Heat-Treating, September 1922, vol. 8, pp. 410-411). The Heppenstall oil-fired furnace for heating ingots and forgings is illustrated and described. The fuel oil is preheated to within 20° of its flash point and is delivered to the burners at 75 lb. pressure. The air is preheated by passing it through U-shaped calorised steel tubes embedded in the air-preheating chamber, and is heated to 600° to 800° F. The furnaces require no stacks, and as combustion is quite complete there is no smoke.

New Design of Continuous Furnace (Iron and Coal Trades Review, February 2, 1923, vol. 106, p. 155). The continuous reheating furnace described was introduced by Priest Furnaces Ltd., and is designed for either producer-gas or semi-gas firing. The furnace has three layers of transverse passages of flues through which the waste gases pass, and two layers of longitudinal passages disposed between the transverse passages, the fuel air, which is supplied under pressure from a fan, passing through the three groups of transverse passages in series and through the flues comprising a group in parallel. The whole of the moving parts are away from the heat, whilst the mechanical parts themselves are of a nature requiring a minimum of maintenance.

W. E. Groume-Grjmailo, *Pit Reheating and Soaking Pit Furnaces* (Iron Age, October 19, 1922, vol. 110, pp. 1013-1014). A discussion of the principles governing the design of soaking pits. In these furnaces, by reason of the height of the heating chamber, it is absolutely necessary that the waste gases should be drawn off as close as possible to the level of the hearth of the pit, otherwise the lower portions of the ingots are plunged into a pocket of stagnant gases and therefore not heated uniformly.

H. R. Simonds, *Forge Shop has New Provisions for Operating Economies* (Iron Trade Review, November 16, 1922, vol. 71, pp. 1347-1350). The author describes modern practice in forging blooms and billets as carried out at the plant of the Kropp Forge Company, Chicago.

F. E. Bash, *Heating and Cooling Curves of Large Ingots* (Paper read

before the American Institute of Mining and Metallurgical Engineers, February 1923). A test was carried out on an ingot 45 inches in diameter to determine the rate at which heat penetrated, and the length of time necessary to bring the whole mass to a forging heat. Temperatures were determined by inserting thermocouples in holes drilled in the end parallel with the axis. Cooling curves were also determined. It took approximately 17 hours to bring the ingot from room temperature to forging heat, at which time the centre was at 2130° F. and the skin temperature 2260° F.

Curves are given showing the difference in temperature between portions of the interior of the ingot as compared with the temperature of the furnace gases.

Ground Type of Bloom-Charging Machine (Iron and Coal Trades Review, May 4, 1923, vol. 106, p. 633). The charger described is in operation at the works of Steel, Peck & Tozer, Sheffield. It charges blooms to the reheating furnace from the press and delivers them to the disc mill.

N. S. Frohman, *Manufacturing Car and Locomotive Axles* (American Machinist, European Edition, November 18, 1922, vol. 57, pp. 473-477). An illustrated account of up-to-date American practice in the manufacture of axles.

E. Kothny, *Manufacture of Alloy Steel for Aircraft Shafts* (Chemical and Metallurgical Engineering, November 22, 1922, vol. 27, pp. 1020-1024). A lengthy abstract of papers dealing with the manufacture of nickel-chromium steel for aircraft construction. The original papers appeared in Stahl und Eisen, January 8, May 20, 1920, vol. 40, pp. 41, 677.

L. S. Cope, *Coarse-Grained Drop Forgings—Their Detection and Correction* (Transactions of the American Society for Steel Treating, May 1923, vol. 3, pp. 808-823). The author reviews the factors which chiefly contribute to a coarse-grained structure in a drop forging. Excessively high forging temperatures with an insufficient amount of mechanical work are the two main contributing factors. The methods of detecting coarse grain in forgings are discussed, together with the various methods of heat treatment.

A. Stubbs, *The Manufacture of Drop Forgings* (Metal Industry, March 23, 30, April 13, 27, May 4, 1923, vol. 22, pp. 287-289, 315-316, 374, 427-428, 454-456).

L. Aitchison, *Drop-Forging Practice* (Lecture before the Association of Drop Forgers and Stampers in Birmingham, November 22, 1922: Forging and Heat-Treating, April 1923, vol. 9, p. 176).

Forming Gear Teeth by Hot Rolling (Iron Age, October 5, 1922, vol. 110, pp. 861-863). A description is given of a machine for the production of gears in one operation. During the rolling of a gear the hot metal blank is gradually worked by an advancing die under 5 to 20 tons pressure. (See also Iron Trade Review, February 9, 1922, vol. 70, pp. 396-399. This Journal, 1922, No. I. p. 594.)

Hot-Rolled Gears (Automobile Engineer, October 1922, vol. 12, pp. 313-315). The article describes the production of gear wheels by a hot-rolling process. The mechanical operations only are dealt with, without reference to the heat-treatment.

W. G. Calkins, *Advantages of the Forged Milling Cutter* (Transactions of the American Society for Steel Treating, November 1922, vol. 3, pp. 239-244, 251). A brief outline is given of the production and treatment of forged milling cutters. The composition of the steels used is as follows: Carbon 0.65 to 0.75; tungsten 17.0 to 19.0; chromium 3.50 to 4.50; and vanadium 0.75 to 1.50 per cent. The forging process, while more expensive, possesses certain advantages as compared with the direct production from bar stock.

Forgings and Smithwork (Metal Industry, February 9, 16, 23, March 2, 9, 16, 1923, vol. 22, pp. 131-132, 155-157, 177-180, 203-206, 231-232, 259-261). A series of articles dealing with forging-shop practice. The selection and testing of materials, typical classes of smithwork, drop-forging, manufacture of forgings from scrap, production of forgings from the ingot, and the manufacture of chain cable are dealt with.

F. H. Colvin, *Modern Methods of Making Shovels of Molybdenum Steel* (American Machinist, European Edition, April 28, 1923, vol. 58, pp. 365-369). An illustrated account of the operations involved in the manufacture of shovels from molybdenum steel.

Rolling-Mill Equipment and Practice. H. E. Davis, *A Motor-Driven Rolling-Mill* (Paper read before the American Iron and Steel Institute, May 25, 1923, 12 pp.). A description is given of a merchant bar mill at the works of the Interstate Iron and Steel Company at South Chicago. It is a continuous roughing and finishing mill, the roughing mill consisting of two 18-inch and four 16-inch stands, driven by a 1500 h.p. three-phase alternating-current motor, and the finishing mill consisting of six stands, driven by a 2000 h.p. alternating current motor.

E. L. Shaner, *Sheet Mills at Lake Port* (Iron Trade Review, November 23, 1922, vol. 71, pp. 1423-1427). An illustrated description is given of the lay-out of the sheet mill of the Ashtabula Steel Co. for the manufacture of black and galvanised sheets. Pulverised fuel is employed exclusively for fuel.

J. E. McDonald, *New Wire Mill has Unusual Features* (Iron Age, May 3, 1923, vol. 111, pp. 1245-1249). An illustrated account of the lay-out and equipment of the new wire mills of the Whitaker Glessner Company, Portsmouth, Ohio.

K. B. Lewis, *Morgan-Connor Continuous Wire Machine* (Iron Age, May 17, 1923, vol. 111, pp. 1409-1412). A survey is given of the development of continuous wire drawing. The Morgan-Connor machine described operates on the flexible principle of the looping mill.

J. D. Knox, *Plant Embodies Modern Practice* (Iron Trade Review,

January 11, 1923, vol. 72, pp. 153-158, 160). An illustrated description is given of the lay-out and equipment of the plant of the Follansbee Bros. Co., at Toronto, Ohio, which comprises open-hearth furnaces, semi-finishing mills, and sheet mills.

E. D'Amico, *A Modern Plant for Rolling Thin Sheets* (Metallurgia Italiana, June 1922, vol. 14, pp. 203-209). The author gives an illustrated description of Boscarelli's new sheet mill installed at the Terni Steelworks.

New Cold-Rolled Steel Strip Plant (Iron Age, October 12, 1922, vol. 110, pp. 920-922). The new plant of the Wallingford Steel Co., Connecticut, U.S.A., is described. The mills are of particularly heavy construction, with housings of cast steel. The two annealing furnaces are of the Smallwood type, and are coal-fired. The material is drawn from the annealing furnaces and cooled under hoods or covers.

Cold-Rolling Mill with Wedge Adjustment (Iron Age, October 5, 1922, vol. 110, pp. 857-858). The new mill for strip steel installed at the plant of the Worcester Pressed Steel Co., Worcester, Mass., is described. Roll adjustment is accomplished by means of wedges, which operate in a direction parallel to the motion of the material between the rolls.

H. S. Thomas, *Tinplate Machinery* (Paper read before the South Wales Institute of Engineers, November 22, 1922: Iron and Coal Trades Review, December 8, 1922, vol. 105, pp. 852-853). The author outlines the developments in tinplate machinery in this country and the United States.

A New Tinplate Doubling Machine (Iron and Coal Trade Review, January 12, 1923, vol. 106, p. 51). The doubling machine described is in operation at the Mellingriffith Works, Cardiff, and is the invention of H. S. Thomas and W. R. Davies.

Mills for Rolling Nickel and Monel Metal (Blast-Furnace and Steel Plant, December 1922, vol. 10, pp. 605-611). An illustrated description of the new rolling-mills at Huntington, West Virginia, for the rolling of Monel metal and nickel sheets. Some details of the refining process of the metals are given.

A. W. MacAulay, *Some Developments in Ball and Roller-Bearing Work, with Particular Reference to Steel Rolling-Mill Plant* (Paper read before the West of Scotland Iron and Steel Institute, March 16, 1923). The author deals principally with the steel used in the production of ball bearings, and refers to recent developments regarding their application to steelworks plant. A typical analysis of ball-bearing steel obtained from Swedish iron is as follows: carbon, 1.01; silicon, 0.25; sulphur, 0.019; phosphorus, 0.02; manganese, 0.28; and chromium, 1.25 per cent. The physical properties obtained from material of this quality were: yield stress, 43.75 tons per square inch; maximum stress, 50.26 tons per square inch; elongation, 24.00 per cent.; reduction of area, 57.9 per cent.

E. Krahnen, *New Electrically Operated Top-Roll Balancing Gear*

(Iron and Coal Trades Review, February 2, 1923, vol. 106, p. 161). A new electrically operated top-roll balancing gear for rolling-mills is described. The screw-down mechanism is of the worm-gear type, acting on the square shank of the down screw, the sliding fit permitting of a free movement of the spindle axially. Around the protruding end of this square shank fits a tube having an external thread of the same pitch as the main screw, which, owing to the sliding fit, can move freely in the axial direction. The nut of this tubular screw takes the form of a cross-beam, to the ends of which are attached two rods forming a top-roll suspension. By means of conical spiral springs an even tension of these rods is assured, sufficient to press the bearing against the breaker, eliminating all back-lash.

J. Smith and L. Rothera, *Electrical Developments in Iron and Steel Works* (Electrician, November 24, 1922, vol. 89, pp. 586-593). An illustrated description is given of the methods introduced in steel-works for the supply of power by electrical means. The Kramer, Scherbius, and Ilgner systems are discussed. It is stated that trials in America show that it is $2\frac{1}{2}$ times as costly to run a steam reversing engine as an electric motor giving equivalent power.

A. Davidson, *Electric Power in Iron and Steel Works* (Electrician, November 24, 1922, vol. 89, pp. 594-596). The advantages of generation and transmission by alternating current are emphasised.

J. MacSheehy, *Electrical Equipment of Steelworks* (Electrician, November 24, 1922, vol. 89, pp. 601-607). Problems involved in the choice of electrical equipment are generally considered. Three-phase generation and transmission with alternating current motors for steady running and conversion to continuous current for motors subject to severe and intermittent loads is the best and most economical system. Details are given of the equipment of a large steelworks arranged on this plan.

J. P. Hodges, *Alternating Current in Steelworks* (Electrician, November 24, 1922, vol. 89, pp. 597-600). In the equipment of steel works there is a tendency to install alternating current machines, and in some cases to replace them with the direct current machines originally adopted. Types of motors and methods of control are discussed in general.

W. McFarlane, *Considerations in the Use of Electricity in Steelworks* (Journal of the West of Scotland Iron and Steel Institute, Session 1922-1923, vol. 30, Part 3, pp. 34-35). The use of electricity for driving steelworks plant, with special reference to the production of electrical energy within the works, is discussed.

G. E. Stoltz, *Improving Rolling-Mill Practice* (Paper read before the Association of Iron and Steel Electrical Engineers: Iron Age, February 8, 1923, vol. 111, pp. 411-414; Iron Trade Review, January 25, 1923, vol. 72, pp. 293-297). The author discusses some of the factors to be considered in the selection of the speed at which a mill is to be operated. The use of direct current electric motors for main roll

drives permits of the proper speed regulation to suit the steel being rolled.

G. E. Stoltz, *Steel Mills with Electric Drive* (Electrical World, July 1, 1922, vol. 80, pp. 6-10). The cost of electric driving is compared with that of steam driving of large rolling-mills, and full particulars of the costs over a series of years are given in two cases. The comparison is very much to the advantage of the use of electric power.

C. A. Ablett, *Economic Principles Governing the Use of Electrical Power in Iron and Steel Works*. (This Journal, p. 225.)

E. Poncelet, *The Speed and Rating of Rolling-Mill Trains* (Revue de Métallurgie, Mémoires, January 1923, vol. 20, pp. 27-31; Iron and Coal Trades Review, March 30, 1923, vol. 106, p. 461). Increasing the speed of the rolls in a rolling-mill by no means accelerates the rolling operation in anything like the same ratio. As Puppe has pointed out the time spent by the bar in a mill is only a small proportion of the time spent in getting ready for a pass, the actual pass not occupying even half the gross time. If this be not taken properly into account time may be actually lost by accelerating the peripheral speed of the rolls. Speed may be increased by reducing the number of the passes, but here again there is a limit to the amount of draft that can be safely put on to the work. The various considerations which govern the rolling-mill operations are considered separately from various points of view, and American and European practice is compared. Programmes are suggested for the rolling of bars, various sections, and plates in mills of various dimensions.

W. Tafel and E. Schneider, *Basis of Rating of Rolling-Mills* (Stahl und Eisen, March 15, 1923, vol. 43, pp. 370-374). Some rules are laid down for judging the standard of efficiency of various types of rolling-mills, by comparing their hourly production over a period of one shift or if necessary, of one week, with the hourly output "without loss," which is found by timing the rolling operations for a brief period during which the mill is working at full power under the best conditions.

R. Gregg, *The Standardisation of Steel Mill Practice through Time Study* (Paper read before American Iron and Steel Institute, May 25, 1923, 19 pp.).

A. H. Dyckerhoff, *Power Problems of Rolling-Mills* (Iron Age, January 4, 1923, vol. 111, pp. 17-21). The stresses of rolling-mill motors, the consequences of over-powering mill drives and the influence of the power factor are discussed.

A. Musso, *An Investigation of the Strains in the Rolling of Metals* (Transactions of American Society of Mechanical Engineers, 1919, vol. 41, pp. 961-970). The author expounds some fundamental principles involved in the rolling of articles of certain definite dimensions, so that the waste of material may be reduced to a minimum. The investigation relates to the mechanical aspect of the question.

F. L. Leach, *The Handling of Material in Steel Mills* (Mechanical

Engineering, August 1922, vol. 44, pp. 493-499). The article describes a large number of mechanical operations involved in the transport of material in steelworks.

Manufacture of Wire.—R. C. Helm, *Use of Liquid Fuel in Metallurgical Furnaces* (Year Book of the American Iron and Steel Institute, 1922, pp. 433-463). This paper contains interesting information on the patenting process used to soften and toughen wire before drawing it through dies, and the types of furnaces used.

G. L. Lacher, *From Ore to Nails in Minnesota Plant* (Iron Age, October 26, 1922, vol. 110, pp. 1057-1063). An illustrated description is given of the lay-out of the new plant of the Minnesota Steel Co., Duluth, for the production of wire products.

A. J. Hain, *Minnesota Steel Adds New Mills* (Iron Trade Review, December 28, 1922, vol. 71, pp. 1773-1778). An illustrated account is given of the equipment of the above plant.

K. B. Lewis, *The Wire-Drawing Die* (Blast-Furnace and Steel Plant, March 1923, vol. 11, pp. 207-209). A short historical account is given of the use of dies for wire-drawing, which dates back for over a thousand years.

Roll-Grinding.—S. S. Shoemaker, *Roll-Grinding Shows Economy* (Iron Trade Review, December 28, 1922, vol. 71, pp. 1765-1768). The author discusses the economy of roll-grinding as compared with roll-turning. A description is given of a massive roll-grinding machine which will handle rolls 40 inches in diameter and 14 feet long. The methods of grinding are outlined.

Manufacture of Tubes.—J. A. Richards, *Manufacture of Solid-Drawn Steel Tubes* (Paper read before the Institute of Marine Engineers, December 12, 1922: Iron and Coal Trades Review, December 15, 1922, vol. 105, pp. 880-881). The author gives an illustrated description of the operations involved in the production of solid-drawn steel tubes. Material for tubes should be very low in sulphur and phosphorus. Billets should be used which have been rolled from comparatively large ingots.

E. Rober, *Producing Iron and Steel Tubes* (Engineering Progress: Iron Trade Review, November 30, 1922, vol. 71, pp. 1481-1484). The various processes for the manufacture of tubes are outlined, and working details are given showing range of each process and dimensions of tubes made.

Plant for Making Small Weldless Tubes (Iron Age, May 17, 1923, vol. 111, pp. 1399-1402). The new equipment of the plant of the Weldless Tube Co., Wooster, Ohio, for the production of small weldless tubes is described and illustrated.

FURTHER TREATMENT OF IRON AND STEEL.

Case Hardening.—F. Hodson, *A New Method of Case-Hardening* (Chemical and Metallurgical Engineering, February 14, 1923, vol. 28, p. 308). This process, which is introduced by A. Gronwall, consists in converting much of the carbonic acid as formed to carbon monoxide. Catalysers of a special metal are placed in the box with the carbonaceous material. The catalyser displaces the equilibrium in such a manner that the amount of CO in the gas is materially increased. With the new method less carbonising material is needed, the temperature can be kept lower than usual, and the time occupied is just about half.

N. Parravano and C. Mazzetti, *Cementation by Means of Boron* (Atti della Reale Accademia Nazionale dei Lincei, 1922, vol. 31, 5th series, pp. 424–425). A piece of steel was heated in a gaseous mixture of boron chloride and hydrogen, as the result of which a coating was deposited on the steel consisting of a very hard alloy rich in boron, capable of cutting glass. The same result was produced by the cementation of nickel in a similar mixture.

E. W. Ehn, *Case-Hardening Plant, Timken Roller-Bearing Co.* (Chemical and Metallurgical Engineering, March 28, 1922, vol. 28, pp. 578–587). A detailed illustrated description of the equipment and methods adopted by the above company for the case-hardening of roller bearings. Special types of furnaces and quenching machines are in use, and the capacity of the plant is over two million parts per day.

J. C. McCullough and H. A. H. Pray, *The Protective Action of Copper in Case Carburising* (Chemical and Metallurgical Engineering, December 6, 1922, vol. 27, pp. 1119–1120). The authors have investigated the use of a plating of copper for preventing carburising action on steel. The results indicate that carbon monoxide gas does not dissolve easily in copper, and hence cannot pass through it unless there are cracks or holes in the plating. Copper platings when applied to clean steel were found to give complete protection against case-hardening, a plating of 0.004 millimetre thickness being sufficient. In the case of non-homogeneous steel, where spots of slag or oxide have come to the surface, the copper coating failed in its effect, as the copper will not deposit on such spots.

Heat-Treatment.—H. B. Knowlton, *Heat-Treatment of the Core of Case-Hardened Articles* (Forging and Heat-Treating, November 1922, vol. 8, pp. 526-528). The author has studied the effect of the carburising heat upon the core of case-hardened steel containing less than 0.25 per cent. of carbon, and the effect of various subsequent heat-treatments upon the structure and strength of the case-hardened piece. The usual carburising temperature is 1600° F., and a temperature much in excess of that has a coarsening effect upon the grain size. The best treatment for a 0.20 per cent. carbon steel to produce the maximum toughness and impact strength is to quench from above the upper critical range, followed by drawing to just below the lower critical range, that is, a draw to about 1300° F. If the drawing temperature is raised to above the lower critical point and the steel is quenched, the toughness will be slightly decreased. It is not possible in case-hardening to give the last quench at a temperature just below the critical point of the core as the case could not be hardened, though the nearer one can come to this treatment the tougher the core will be. It is therefore best, from the standpoint of producing a good core, that the last quench be given from the lowest temperature which will harden the case.

A. Portevin, *Variations of Capacity Accompanying the Thermal Treatment of Hollow Steel Bodies* (Comptes Rendus, March 26, 1923). The author presents a study of the influence of the quenching and tempering temperature and rate of cooling on the changes of capacity of steel shells.

A. Portevin, *Quenching of Steel and Alloys* (Revue de Métallurgie, Mémoires, December 1922, vol. 19, pp. 717-740). A general review of the heat treatment of metals.

A. Portevin, *Reduction and Elimination of Stresses in Steel by Reheating and Subsequent Slow Cooling* (Comptes Rendus, November 1922, vol. 175, pp. 959-961). Small cylinders of steel were heated at temperatures not exceeding 650° C. for one hour and were allowed to cool very slowly. Examination showed that the longitudinal stresses were diminished by 25 per cent., when the metal is reheated to 200° C., and by 50 per cent. at 350° C., whilst at 600° C. the stresses are reduced to a negligible amount. The first two temperatures are below the annealing temperature necessary to cause softening of quenched steel.

L. K. Marshall, *Tool Steel Manipulation* (Transactions of the American Society for Steel Treating, October 1922, vol. 3, pp. 90-93). The author outlines some of the more important points in the heat-treatment of tool steel.

N. B. Hoffman, *A Metallographic Study of Hollow Rock Drill Steel, as influenced by the Method of Manufacture* (Transactions of the American Society for Steel Treating, January 1923, vol. 3, pp. 436-446). A brief description is given of the present methods of manufacture. Until the last two years practically all rock drills used were made of

carbon steel, but the gradual increase in size of drilling machines led to the application of alloy steels. The steel found to give excellent results in actual practice is a vanadium steel of the following composition: Carbon, 0.78 to 0.85; manganese, 0.25 to 0.35; phosphorus under 0.020; sulphur under 0.025; silicon, 0.12 to 0.16; and vanadium, 0.20 per cent. It has given from two to three times the life in endurance tests and actual service of carbon steel. In the pierced and rolled or drawn bar the area of metal surrounding the hole is decarburised to various depths, and is often full of minute cracks or folds from which detailed fractures commence and spread rapidly.

C. Y. Clayton, *Hardness and Heat Treatment of Mining Drill Steel Shanks* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). The hardness of mining drill shanks varies between 196 and 782 Brinell, the greater number of steels showing values between 364 and 444. Methods of heat treating vary not only between different mines but also between different blacksmiths at the same mine. Water, oil, and air are the quenching media used. A standard method of heat treating must be adopted by each shop if drill shanks are to give satisfactory service.

H. S. Brainerd, *Heat Treatment of Drill Steels* (Compressed Air Magazine, New York; Mining Journal, December 9, 1922, vol. 139, p. 919). Little or no attention is ever given by the user of drills to their proper heat treatment, and many failures are due to incorrect treatment in the blacksmith's shop. The author lays down the exact procedure to be followed in forging the steel and subsequently hardening it.

R. J. Day, *Rock Drill Steel* (Engineering and Mining Journal Press, April 14, 1923, vol. 115, pp. 670-673). The author deals with the various types of bits and shanks in general use and discusses their design and heat treatment.

F. C. Langenberg, *Heat Treatment of Steel Castings* (Iron Age, February 8, 1923, vol. 111, pp. 397-400). An account is given of a number of experiments carried out at the Watertown Arsenal. The effect on impact values of electric and open-hearth steel was studied. Although experiments prove that physical properties, including resistance to impact, of cast steel of a given composition can be materially improved by quenching and drawing, it is not advisable to prescribe in a general specification a set of physical properties which cannot be obtained by a simple annealing treatment. Interior defects and irregularities of steel castings are very apt to make the quenching operation exceedingly dangerous as regards development of cracks, it being practically impossible to quench castings of certain design without development of cracks which may not always be apparent upon surface examination. A casting which has been quenched and drawn can be very advantageously used for many purposes if the design will permit of its proper treatment. In case the heat treatment of a given casting is desirable in order to obtain

better physical properties, a study should be made of the casting in question and special physical requirements and specifications developed for each individual case.

H. A. Neel, *Heat Treatment of Steel Castings* (Paper read before the American Foundrymen's Association, May 3, 1923). The paper gives the results of an investigation to determine specifically the proper heat treatment to apply to electric steel castings of 0.2 to 0.3 per cent. carbon. The scope of the research was limited to thin sections 1 inch or less in thickness.

H. C. Ihlen, *Heat Treatment of Steel Castings* (Blast-Furnace and Steel Plant, January 1923, vol. 11, pp. 95-99). The characteristics of steel castings in the raw and in the heat-treated conditions are discussed, and micrographs of their structure are shown, with consideration of the correct treatment in relation to size and the composition of the casting.

A. W. Lorenz, *Heat Treatment of Alloy Steel Castings* (Paper read before the American Foundrymen's Association, May 3, 1923). The influence of heat treatment on steel castings is dealt with, and the results of heat-treating practice on nickel-chromium steel castings are given.

E. D. Smith, *Hardened and Tempered Malleable Castings* (Paper read before the American Foundrymen's Association, May 2, 1923). Particulars are given of an investigation undertaken to determine the possibilities of hardening malleable castings. While the experiments were not carried to a definite conclusion, they showed that there are great possibilities for further investigation.

T. D. Lynch and W. J. Merten, *Tests showing the Effect of High Temperatures in Malleable Iron* (Transactions of the American Society for Steel Treating, May 1923, vol. 3, pp. 833-840). The results are given of a number of tests made upon malleable iron castings after they had been subjected to various high temperatures. The susceptibility of structural changes of malleable iron at high temperatures is shown. The authors recommend the use of high annealing temperatures, from 900° to 925° C., for malleablising when it is desired to obtain high-grade material with a high degree of ductility from annealing charges representing different chemical analyses. The tests demonstrated the fact that it is possible to reheat malleable iron to the proper temperature without destroying its malleablised structure; however, too high a temperature will re-establish white, hard, and brittle structure. Accelerated cooling appears to be conducive to finer grained ferrite and therefore a tougher and more ductile material.

Heat-Treating Motor Castings (Foundry, February 1, 1923, vol. 51, pp. 108-110). An illustrated description of the equipment and methods employed at an American plant for heat-treating motor-car engine castings. The castings are heated in a tunnel furnace of the muffle type at a temperature of from 750° to 800° F.

O. E. Harder, *Improvement in Crusher Steel is suggested by Metallo-*

graphic Tests (Engineering and Mining Journal Press, February 17, 1923, vol. 115, pp. 314-318). An examination of parts of a jaw, gyratory and roll crushers that had failed in service indicates that sufficient attention is not given to heat treatment in the process of manufacture.

B. Egeberg, *The Heat Treatment of Cast Steel for Hydro-electric Power Machinery* (Transactions of the American Society for Steel Treating, January 1923, vol. 3, pp. 422-429). The castings used in the manufacture of this class of machinery in Norway are all made of electric cast steel with about 0.20 per cent. carbon. The method of heat treatment is outlined. Castings weighing up to 8 tons are treated in an electric annealing furnace, larger castings in an 80-ton furnace heated with producer gas. The castings for hydro-electric power machinery are usually of an intricate shape, and therefore are liable to warp if not cooled evenly.

The furnaces are fitted with air inlets in the roof, connected to a strong blower having large air volume and low pressure. By this arrangement the steel can be cooled down to below the critical point A_1 in a comparatively short time.

O. Z. Klopsch and H. F. Roberts, *Migration of Carbon from Steel to Ingot Iron* (Transactions of the American Society for Steel Treating, May 1923, vol. 3, pp. 855-863). The authors have investigated the rate of migration and the depth of penetration of carbon which takes place between eutectoid carbon steel and ingot iron when heated at various temperatures and for various periods of time. In order to prevent the escape of carbonaceous gases an ingot iron cylinder was drilled part way through longitudinally and a steel plug inserted, and a plug of ingot iron used to seal the drill-hole. The heating of the specimens was carried out in an electric furnace of the resistance type.

The temperatures used were above the Ac_3-2-1 range of the eutectoid plug and above the Ac_2 point of the ingot iron. To determine quantitatively the amount of carbon which had migrated, the samples were cut transversely, polished, etched, and photographed. The results show that with close physical contact, oxygen being excluded, fairly accurate quantitative results are obtainable. A tapered plug driven into a tapered hole should give better results than a cylindrical plug shrunk into a ring, when such shrinking causes oxidation. Migration of carbon takes place from the steel plug to the ingot iron cylinder at temperatures above the Ac_3-2-1 range of the plug in measurable quantities.

C. F. Smart, *Steel is Steel* (Transactions of the American Society for Steel Treating, December 1922, vol. 3, pp. 299-306, 334). The author draws attention to the need of careful classification and selection of steel for heat treatment based on chemical and metallurgical inspection. The results are given of a number of tests showing the difficulty of obtaining a uniform product in heat-treating steels of the same type but from different heats.

W. J. Merten, *The Use of Molten Salts in Heat-Treating* (Forging and Heat-Treating, March 1923, vol. 9, pp. 148-150). The importance of protecting finished steel parts from oxidising gases during heating is emphasised, and notes are given as to the selection of proper salts for the avoidance of pitting and decarburisation. It is essential that the bath should be free from impurities.

J. A. Jones, *The Action of Salt Solutions on Mild Steel* (Chemical Trade Journal, 1922, vol. 70, pp. 323-325). One of the chief factors in the production of cracks is the presence of either internal or applied stresses which must exceed definite values. Tests were carried out with solutions of calcium nitrate, potassium hydroxide, ammonium nitrate, and sodium nitrate. The first cracks were formed in those plates which were thought to have the greatest internal stress. These stresses were gradually reduced by annealing, but cracks still appeared. A similar action of caustic alkalies was found. In all cases the cracks produced were intercrystalline. It was concluded that the solutions of nitrates yielded a product having such an action on the intercrystalline material that the intercrystalline cohesion is reduced.

S. Tour, *Salt Baths for Heat-Treating* (Transactions of the American Society for Steel Treating, November 1922, vol. 3, pp. 245-251). The author discusses the different combinations of salts used in heat-treating operations. Most of these combinations have some objectionable quality, and are generally eutectic mixtures of metallic chlorides, such as calcium chloride, barium chloride, sodium chloride, and potassium chloride. The ideal salt would be one which gave no pitting action, which gave the maximum life of the pot, and would not necessitate careful washing of the steel after quenching. According to the author, such a salt has not yet been found.

Heat-Treatment Furnaces.—F. W. Brooke, *Methods of Handling Materials in the Electric Furnace and the Best Type of Furnace to Use* (Paper read before the American Electrochemical Society, May 1923). The author discusses, in general, the design of various electric heat-treating furnaces, and refers to their advantages and disadvantages. Attention is drawn to the method of handling materials, so that a uniform temperature and high furnace efficiency may be maintained. The types of furnaces dealt with are the plain box type, the special box type, the car type, the recuperative and continuous furnaces.

C. L. Ipsen, *Selection of Electric Furnaces for Steel Treating* (Transactions of the American Society for Steel Treating, April 1923, vol. 3, pp. 720-728). With improved design and an increase in the cost of gaseous, liquid, and solid fuels the electric furnace is coming into use more and more. The many advantages of these furnaces are outlined.

Continuous Annealing Furnaces for Sheets (Iron Age, November 23, 1923, vol. 110, pp. 1342-1343). A description is given of the continuous
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furnaces for box annealing installed at the plant of the Ashtabula Steel Co., Ohio. The furnaces are of the underfired car type, with a daily capacity of 125 tons each, using pulverised coal as fuel.

P. Dressler, *Tunnel Kilns for Annealing Malleable Castings* (Paper read before the American Foundrymen's Association, May 2, 1923). The construction, operation, and control of tunnel kilns are described, and details are given of how the process of heating and cooling can be kept under complete control.

W. Trinks, *Electrically Heated Industrial Furnaces* (Forging and Heat-Treating, December 1922, vol. 8, pp. 538-542). Various types of electrically heated furnaces are illustrated and described, and special designs of heating elements are shown.

R. W. Newcomb, *A New Type of Automatic Temperature Regulator and its Application to Heat-Treating Furnaces* (Transactions of the American Society for Steel Treating, October, 1922, vol. 3, pp. 98-102). The regulator described is adaptable to either gas, oil, powdered coal, or electricity, and the apparatus is entirely automatic.

A. D. Frydendall, *Combustion as it Pertains to Industrial Heat-Treatment Furnaces* (Transactions of the American Society for Steel Treating, May 1923, vol. 3, pp. 824-832). The various types of fuels which are used in heat-treatment furnaces are dealt with, and the advantages and disadvantages in their use are pointed out.

W. C. Buell, *Heat Salvage in Small Furnaces* (Chemical and Metallurgical Engineering, April 9, 1923, vol. 28, pp. 638-641). The application of recuperators to small heating furnaces is dealt with. In one instance where a tool furnace was fitted with a simple design of recuperator, a fuel saving of 30 per cent. was effected. Certain metals with their high thermal conduction and relatively low cost are the best for use in their construction. Calorised steel pipe is most suitable for this purpose.

J. W. Smith, *Gas Useful in Heat-Treating Room* (Transactions of the American Society for Steel Treating, January 1923, vol. 3, pp. 396-414). The use of town gas for heat-treating operations is discussed, and various types of burners and furnaces are illustrated. The wide application and accessibility of town gas has shown that it can be used economically and efficiently and compares favourably with other types of fuel.

Welding and Cutting.—F. B. Shenstone, *Electric Welding* (Transactions of Institution of Engineers, Australia, 1921, vol. 1, pp. 397-431). The various systems of electric welding are discussed, and the arc system with negative bare electrodes is particularly dealt with. The results of some physical and mechanical tests of electric welds are given, with micrographs showing the structure of the welds.

D. N. Louis, *Electric Arc Welding* (Electrical World, July 29, 1922, vol. 80, p. 231). A table is given showing the approximate value for horizontal butt welds on steel plates using bare electrodes and direct

current. The current values for lap welds and strap welds can be found by multiplying the first value by a constant.

H. W. Wolton, *Electric Welding* (Proceedings of the Staffordshire Iron and Steel Institute, 1922-23, vol. 37, pp. 64-73). A general account of electric welding practice, by the methods of arc welding and resistance welding.

W. H. Namack, *Electric Welding of Cast Iron* (Journal of American Welding Society, November 1922, vol. 1, pp. 7-33). The report gives the results of an investigation carried out by a committee to determine the best method of welding cast iron. It deals with the preparation of the parts to be welded, slag inclusions, the strength of current, method of deposition of the material of the electrodes, and testing the welded pieces.

Problems in the Welding of Cast Iron (Iron Age, October 12, 1922, vol. 110, pp. 929-930). At the Chicago Meeting of the American Welding Society held in October 1922, a number of reports were presented dealing with the welding of cast iron. In the joint report of the Gas, Electric, and Thermit Welding Research Committees, the general properties of cast iron, in so far as they affect weldability, are dealt with. The use of acetylene for cast iron welding is dealt with in a report by S. W. Miller, and the report by W. H. Namack dealt with arc welding.

J. Caldwell, *Electric Arc Welding Apparatus and Equipment* (Journal of the Institution of Electrical Engineers, February 1923, vol. 61, pp. 253-277; Engineer, December 29, 1922, vol. 134, pp. 689-690). The various types of apparatus and equipment for welding work are described. Good welding can be done with both direct and alternating current, and the best electrical conditions for either system are indicated. Flux-covered electrodes are essential for alternating current, apparently because the lagging effect of the flux and slag maintains the necessary temperature during the periodical current reversals. The striking of the arc is rather more difficult with alternating current.

A. S. Kinsey, *Oxyacetylene Torch Cuts Iron* (Paper read before the American Welding Society: Foundry, April 15, 1923, vol. 51, pp. 328-330). The application of the oxyacetylene torch to the cutting of cast iron is dealt with. The large percentage of impurities in cast iron has hindered the development of a successful gas-cutting process, but a new design of torch has been perfected which enables the metal to be cut readily.

H. S. Smith, *Operating Oxyacetylene Apparatus* (Iron Trade Review, December 7, 1922, vol. 71, pp. 1557-1561). The author discusses safety precautions necessary in oxyacetylene welding practice, with special reference to generators, storage of calcium carbide, gas and air tanks, and methods of making connections.

A. M. Candy, *Cutting Metals with the Electric Arc* (Iron Age, April 19, 1923, vol. 111, pp. 1098-1099). The time required and the speed of

cutting of metals with the electric arc are shown. Graphite or carbon electrodes are usually employed.

F. A. Parsons, *Power required for Cutting Metals* (Mechanical Engineering, January, 1923, vol. 45, pp. 35-41). An investigation has been carried out for the purpose of determining the fundamental laws governing milling, turning, planing and drilling operations on the various metals and alloys used in engineering construction. The following variables have been studied: The efficiency of the machine, the rate of metal removal, the average thickness of the cutting before distortion, the front rake on the cutting blade, the material being cut, the spiral angle or shear on the cutting tool, the condition of the cutting tool, sharp or dull. The results are presented in the shape of formulæ and tables by means of which the power required to machine metal may be calculated and an example of their use is worked out in detail.

Chains.—H. R. Simonds, *Producing Detachable Cast Chain* (Iron Trade Review, February 8, 1923, vol. 72, pp. 446-449). An illustrated account is given of the operations involved in the production of malleable cast iron links for detachable chain. The old method of hand assembling the links is still used extensively, but the introduction of the assembling machine makes possible an output three times greater than with the hand method. The casting, finishing, annealing, and assembling operations are described.

PHYSICAL AND CHEMICAL PROPERTIES.

Properties of Cast Iron.—*Test-Bars* (Foundry Trade Journal, February 22, 1923, vol. 27, pp. 151–155). Test-bars for all castings can only be comparative, and never under foundry conditions give the actual strength of the casting. The whole of grey iron and malleable foundry practice is based on graphitisation, and test-bars should go through this process to be representative of the casting. Chilling or densening of cast test-bars has the effect of hastening the cooling, with the result that they do not go through the same range of cooling at the same speed as the castings. This quicker cooling gives an entirely different structure from that in the casting, more pronounced in cast iron than other materials. It is considered that three test-bars of different sections will be more representative of a grey iron casting than one size.

S. G. Smith, *The Value and Relation of Test-Bars to Castings* (Foundry Trade Journal, March 29, 1923, vol. 27, pp. 248–250).

O. Smalley, *The Effect of Special Elements on Cast Iron* (Paper read before the Institution of British Foundrymen : Foundry Trade Journal, December 21, 1922, January 4, 1923, vol. 26, pp. 519–522, vol. 27, pp. 3–6). The author deals with the carbon problem of cast iron and gives the results of an investigation on the effect of special elements, such as copper, nickel, chromium, molybdenum, and tungsten on the quantity and form of the graphite. The commercial possibility of direct manufacture of alloy malleable castings from the cupola is also considered. The experiments demonstrate the relative values of the special elements as denseners of common soft grey cast iron, and suggest that the introduction of small quantities of copper, nickel, chromium, and molybdenum are efficacious in helping to eliminate coarseness of texture and sponginess.

R. Moldenke, *Effect of Nickel-Chromium on Cast Iron* (Paper read before the American Institute of Mining and Metallurgical Engineers, September 1922). The results are given of a series of tests of cast iron made of varying mixtures containing up to 20 per cent. of Mayari pig iron. This pig iron contains a considerable content of nickel and chromium. When remelting in the cupola, the nickel is hardly affected, while the chromium is oxidised and removed to some extent. In the tests described, melting was done in a crucible furnace and transverse test-bars poured. Breaking strength and deflection, Brinell hardness, tensile strength, and chemical composition were determined for each heat, and a series of graphs is given showing the effect of composition on these physical properties. The curves show that the Brinell

hardness decreases as the total carbon increases. Hardness and transverse strength also seem to be independent properties. The nickel-chromium definitely increases hardness with rising percentages. The increase is not large, but it shows that the softer irons may be obtained with higher total carbon percentages, and can be kept strong enough by holding the graphite down with the low silicon ranges.

A. E. M. Smith, *Notes on Grey Cast Iron* (Paper read before the Institution of British Foundrymen: Foundry Trade Journal, April 5, 1923, vol. 27, pp. 270-272). The influence of carbon, silicon, phosphorus, sulphur, manganese, aluminium, and titanium on cast iron are described.

W. R. Webster, *The Physics of Cast Iron and its Bearing on all Cast Iron Products and Specifications for Cast Iron Products* (Proceedings of the American Society for Testing Materials, 1922, vol. 22, Part 2, pp. 217-226). Suggestions are made for furthering the work of setting up suitable specifications for cast iron. The author points out the importance of reducing to a necessary minimum the great variety of chemical compositions of pig iron used in the manufacture of steel, grey iron, and malleable castings. A note by R. Moldenke on a scheme for the study of the physics of cast iron is appended to the paper.

O. Bauer, *Pearlitic Cast Iron, its Manufacture, Strength, Properties, and Applications* (Stahl und Eisen, April 26, 1923, vol. 43, pp. 553-557). A method is outlined for the production of a pearlite-graphite structure in castings. Such material is stated to possess good bending and tensile strength and toughness, high resistance to shock, moderate hardness with good machining qualities, great resistance to sliding friction, little tendency to formation of blowholes, and a fine dense structure which is unaffected by temperature changes.

J. W. Bolton, *Phosphorus Formations in Iron* (Foundry, October 1, 1922, vol. 50, pp. 787-791). Complete details of the microscopic study of the phosphorus structure in cast iron are given. It is shown that steadite in commercial grey irons exists as a series of phosphorus-rich alloys rather than as the definite cellular eutectic form. Theories on the effects of the phosphorus net work are contradicted and new ideas are submitted. Etching methods are outlined and the use of ammonium persulphate and of liquid bromine in amyl alcohol as etching reagents is dealt with.

J. Durand, *Changes in Volume of Cast Iron Due to Heating* (Comptes Rendus, 1922, vol. 175, pp. 522-524). A study of the conditions which cause an increase in the volume of cast iron has been carried out, with a view to determining the relative importance of the various factors affecting it. The measurements were performed by means of a dilatometer, the samples used being 50 millimetres in length and 8 millimetres in diameter. A diagram shows the growth of a specimen of known composition subjected to temperatures ranging from 600° to 900° C. The increase becomes smaller on each successive heating, as the amount of free graphite deposited, which causes the increase in

volume, is less at each stage. As the growth varies inversely with the rate of heating and directly as the silicon content, it is only of importance when the silicon is high and the casting is heated slowly.

T. E. Hull, *Growth and Deterioration of Grey Cast Iron under Repeated Heatings* (Paper read before the West Yorkshire Metallurgical Society : Foundry Trade Journal, November 16, 1922, vol. 26, pp. 412-414). The results of previous investigators are reviewed and the chief factors in the growth and deterioration of cast iron are summarised. The oxidation of the silico-ferrite and the consequent expansion of the products of oxidation must account for the major increase in bulk of the iron in the early stages of growth. The occluded gaseous constituents of the iron are no doubt the prime factor in the early growth of the metal. The element phosphorus, and its distribution, whilst being a contributory cause of growth to a very small extent, is no doubt sometimes responsible, when present in sufficient quantity, for the production of the cracking and the break-up of the material under these influences. In cases approaching total expansion the free iron is oxidised and accounts for maximum growth.

E. P. Poste, *The Relative Merit of Heat-Resisting Alloys for Enamel-Burning Racks* (Journal of American Ceramic Society, November 1922, vol. 5, pp. 811-816). Enamel-burning racks fail by oxidation and warping. Several alloys have been tested at temperatures of 1700° to 1800° F., and these are listed in the order of increasing warpage and increasing oxidation. The most resistant to warpage are calite, hardite, nichrome; and to oxidation, thermalloy, hardite, nichrome. Cast iron, cast steel, and basic open-hearth steel are the lowest in both lists.

F. Wever, *The Nature of Graphite and Temper Carbon* (Mitteilungen a.d. Kaiser-Wilhelm Institut für Eisenforschung, 1922, vol. 4, pp. 81-86). The investigation had for its object the determination of the nature of the elementary carbon in commercial irons, and for the purpose various specimens of pure carbon and several kinds of grey pig iron were used, namely, natural graphite, graphite from coke pig iron, graphite from charcoal pig iron, graphite from grey cast iron, temper carbon, blast-furnace coke, and firwood heap charcoal. These several kinds of carbon show no difference in their crystalline structure. They represent the same allotropic form in different degrees of dispersity. The structure of graphite in grey cast iron is independent of the kind of fuel used in smelting it. The mean crystal size, measured by Scherrer's method, was calculated to be :

For graphite from grey iron	100 × 10 ⁻⁸ cm.
Temper carbon	30 to 50 × 10 ⁻⁸ cm.
Coke and charcoal	10 × 10 ⁻⁸ cm.

The lamellæ of the eutectic graphite consist of a large number of ultra-microscopic crystals. The view of Debye and Scherrer, according to which the lattice of the graphite is very easily subject to deformation by mechanical influence, was not confirmed. On the contrary,

the severest mechanical working failed to produce any noticeable disturbance of the space lattice, and the effect observed by Debye and Scherrer is probably attributable to some pronounced directive effect.

J. F. Harper and R. S. MacPherran, *Annealing Grey Cast Iron* (Paper read before the American Foundrymen's Association, June 1922 : Iron Age, October 19, 1922, vol. 110, pp. 1007-1009). The results are given of an investigation carried out in order to determine the correct time and temperature for annealing grey iron castings, and to determine the effect of annealing and quenching on the physical properties. The results of annealing for a period of one hour indicate no loss of strength at 1150° F., or material decrease in Brinell and scleroscope hardness. At 1250° F. there is a slight drop in physical properties as well as hardness. The temperature of 1150° F. for one hour should not be exceeded when annealing to relieve machine or casting strains. When annealing to increase machinability, only temperatures of from 1450° to 1550° F. are satisfactory.

A. Hayes, W. J. Diederichs, and W. M. Dunlap, *Experiments on the Rapid Graphitisation of White Cast Iron and a Theory for the Mechanism of Graphitisation* (Transactions of the American Society for Steel Treating, March 1923, vol. 3, pp. 624-637). Various heating and cooling treatments were applied to specimens of white cast iron for varying periods of time ranging from one to sixty hours. Photomicrographs show typical structures obtained. The physical properties of the specimens are also discussed. The authors have formulated a theory for the mechanism of the graphitising action.

A. E. White and H. E. Gladhill, *The Influence of Temperature and Composition on the Graphitisation of White Cast Iron* (Transactions of the American Foundrymen's Association, 1922, vol. 30, pp. 413-419).

Tests and Properties of Steel.—A. Mesnager, *Deformation and Fracture of Solid Materials* (Revue de Métallurgie, Mémoires, June, July, 1922, vol. 19, pp. 366-378, 425-436). The work of many authorities on the properties and testing of materials is reviewed. The author concludes that the theories at present held concerning the elastic limit of such materials as mild steel and copper are incorrect, and that the elastic limit appears to be entirely a function of the principal shear. It is of prime importance to distinguish between equilibrium failures which cause permanent deformation and those which cause fracture. The same body may be brittle or plastic, according to the forces to which it is subjected. The laws of deformation of metals are analogous to those governing the deformation of quite different bodies.

H. A. Holz, *Recent Researches on the Elastic Limit* (Transactions of the American Society for Steel Treating, January 1923, vol. 3, pp. 367-385). The paper points out some of the fallacies in the use of the elastic limit, proportional limit, yield point, and maximum strength as an indication of the behaviour of metals in practice. The various types of machines or apparatus for determining these properties

are discussed, and a detailed description is given of the latest type of extensometer. This instrument, designed by Professor Dalby, operates on a principle similar to a mirror galvanometer in which the beam of light reflected by the mirror traces a path on a photographic plate. This principle eliminates the pencil friction of some of the older types of stress-strain curve-plotting apparatus. The results obtained with the instrument permit the study of certain peculiarities in the stress-strain diagrams of metals and alloys which were obscured in the diagrams plotted by earlier instruments. Numerous stress-strain diagrams of various ferrous and non-ferrous metals are given.

F. Körber and R. H. Sack, *Comparative Static and Dynamic Tensile Tests* (Mitteilungen a.d. Kaiser-Wilhelm Institut für Eisenforschung, 1922, vol. 4, pp. 11-29). The investigation was carried out on four plain carbon steels containing the following percentages of carbon: 0.08, 0.20, 0.63, 0.86; the phosphorus was in all cases 0.01 per cent. and the sulphur was 0.002, 0.018, 0.01, and 0.01 per cent. in the respective specimens. From a comparison of the results of ten static and dynamic tests the following conclusions were drawn: Elongation and contraction are practically independent of the speed of rupture, except in the high-carbon steels, where the dynamic elongation and contraction exceed the static. The specific work producing fracture and the tensile stress manifested in the dynamic test are always greater than in the static test. The difference in the values obtained increases with increasing carbon content, and in the case of two high-carbon steels the difference increases as the length of the test-bar is diminished. Notched-bar impact tests were not carried out, but for the impact tests bars of special form are recommended, the dimensions of the test-pieces being 5 millimetres diameter, and the lengths being 50, 25, and 5 millimetres. The results were not affected by reducing the speed of impact to one-half. Impact tests on bars of different diameters proved that the law of similarity holds good in the case of plain bars, whereas it has been established that it does not hold good in the case of notched bars, for the reason that the notched-bar impact test relates only to the cross section at the point of fracture, and not to the volume.

R. Mailänder, *Static and Dynamic Compression and Tensile Tests* (Kruppsche Monatshefte, February-March 1923, vol. 4, pp. 39-51). A series of experiments on the comparative effect of static and dynamic tests confirms in general the observations of previous investigators. It requires a greater expenditure of work to produce the same amount of compression in a metal cylinder with a single blow than with a static pressure. For small amounts of compression the proportion is as high as 2:1, but the ratio diminishes with increasing compression. In impact tensile tests the smaller the force of impact employed, the greater is the expenditure of work to produce fracture. Impact tensile tests give about the same amount of contraction of area as static tensile tests, but the elongation is greater under the former test except in the case of manganese steels; under several light blows

the elongation is greater than under a single blow producing fracture. If the cylindrical length of a test-bar is long in proportion to the diameter (over 10 to 1), a tensile test performed by a single blow may produce several contractions in the bar, and the material between such contractions shows little or no strain effect.

J. Seigle, *The Permanent Deformations of Steels by Tension, Bending, and Torsion* (Revue de l'Industrie Minérale, Mémoires, December 15, 1922, pp. 655-673). An illustrated account of experiments on both mild and hard steel bars and tubes, undertaken to ascertain the changes they undergo on fracture and the practical application of the results.

J. Seigle, *The Principal Characteristics of Mild Steel Bars Broken by Traction* (Comptes Rendus, September 1922). The view is generally held that a steel hardened by cold-drawing is brittle and dangerous to use. Tests on bars of steel broken by pulling show that this opinion is not strictly true.

J. Seigle, *Permanent Deformation of Wire Broken on Wire Tension-Test Machines* (Revue de l'Industrie Minérale, Mémoires, February 1, 1923, pp. 65-74). Describes a series of experiments on the fracture testing of wire. Wire breaks in tension, not because it cannot, theoretically, adjust itself almost indefinitely to the tensile stress, but because the elongation does not, in practice, conform to the tensional demand but, owing to heterogeneity of structure, or lack of geometrical symmetry, it breaks before the true elongational capacity is reached. By gradually applied stresses, astonishingly high results can be obtained, and these are illustrated in a series of stress-strain diagrams.

J. Seigle, *Tests on High-Tension Drawn Steel Wires* (Revue de l'Industrie Minérale, February 15, 1923, pp. 105-110).

C. Frémont, *The Cause of the Formation of the Elongation at Constant Load near the Elastic Limit in Testing Mild Steels* (Comptes Rendus, February 5, 1923).

A. H. Strang and L. R. Strickenberg, *Results of Some Compression Tests on Structural Steel Angles* (United States Bureau of Standards, 1922, Technologic Paper 218). The object of the tests was to determine the ultimate compressive strength of steel angles fastened at the ends in such a way as would closely correspond to their connections in the construction of transmission towers.

Malaval, *The Elastic Limit of Steels* (Revue de Métallurgie, Mémoires, January 1923, vol. 20, pp. 46-48). A note on the elastic limit as affected by the simultaneous application of several stresses of varying nature. The enquiry was originally directed to elucidate the conditions which might be expected to occur in pieces of artillery subjected to the interplay of tensional and compressive forces acting in different directions at the same time. A formula is given in which a value is assigned to a coefficient n which is such that under the influence of unit tension T and compression P causing elongation, $T + nP =$ the elastic limit. In this case, of course, T and P are at right angles to one another.

K. Wendt, *Requirements and Properties of Structural Steel* (Kruppsche

Monatshefte, June 1922, vol. 3, pp. 121-167: Paper read before Verein deutscher Ingenieure. See *Journal of the Iron and Steel Institute*, 1922, No. 2. p. 358).

Z. Jeffries and R. S. Archer, *Mechanical Properties of Commercial Iron* (Chemical and Metallurgical Engineering, October 4, 1922, vol. 27, pp. 694-697). Deals with the mechanical properties of iron as observed by the ordinary methods of testing, and the particular properties which specific methods of testing serve, or are intended to reveal. From this point of view even the simplest test is complicated by the many variable factors operating. Detailed analytical investigation of the nature of the common mechanical properties of metals, and definitions of the more fundamental properties, are needed. A classification is made on these lines, in the course of which attempts are made to define the causes of hardness and strength, the nature of plasticity, and the influence of rate of loading on the mechanical results of tests.

J. Montgomerie, *Elastic Properties of Riveted Joints* (Paper read before the Institution of Naval Architects: Iron and Coal Trades Review, April 13, 1923, vol. 106, p. 533). The results are given of an investigation of the elastic properties of riveted joints. The pull in tons at which slip occurred was ascertained for a great variety of joints, for both steel and iron rivets closed hydraulically, pneumatically, and by hand.

F. C. Lea, *Effect of Temperature on some Properties of Metals* (Proceedings of Institution of Mechanical Engineers, 1922, vol. 2, pp. 885-904). Results are recorded of a large number of mechanical tests of various metals and alloys under varying temperature conditions. A special study is made of Armco iron. It is shown that below 250° C. the effect of temperature, particularly on steels, is not serious where that limit is not exceeded, but it must not be assumed that steel alloys can be relied on to behave similarly.

F. C. Lea, *Tensile Tests of Materials at High Temperatures* (Address to the Junior Institution of Engineers: Engineer, February 16, 1923, vol. 135, pp. 182-183). A discussion of the usual data obtained from a tensile test specimen at ordinary temperature, and the effect of higher temperatures on these. It is shown that at a certain temperature a mild steel specimen can be, for a particular cycle of stress, practically elastic over a total range of stress six times as great as the limit of proportionality (elastic limit) indicated in a tensile test.

H. J. French, *Effect of Temperature, Deformation, and Rate of Loading on the Tensile Properties of Low-Carbon Steel below the Thermal Critical Range* (U.S. Bureau of Standards, 1912, Technologic Paper No. 219. See this Journal, 1922, No. II. pp. 371-372).

H. M. Howe, F. B. Foley, and J. Winlock, *Influence of Temperature, Time, and Rate of Cooling on Physical Properties of Carbon Steel* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). The investigation was carried out under the auspices of the Committee of the National Research Council.

Steels of 0.34, 0.52, and 0.75 per cent. carbon were subjected to various temperatures above A_{c3} , held for 10, 60, and 120 minutes, and cooled at various rates; after which their tensile properties, hardness, and resistance to impact were compared. Mainly for purposes of comparison of physical properties, some of the 0.52 carbon steel was quenched in water from different temperatures above A_{c3} , and drawn at a number of temperatures below A_{c3} . The same steel was also subjected to repeated heatings and the physical properties determined. The results are summarised as follows: Increasing T_{max} . (above A_{c3}) produces austenite with progressively finer and more uniformly distributed carbon, which when cooled at such a rate as to produce pearlite, causes an increase in the hardness of high carbon hypoeutectoid steel. The uniformity of distribution of the carbide in the ferrite-carbide aggregate is a function of T_{max} ., and finer pearlite lamellæ are expected to result, with a given cooling rate, from austenite in which the carbon was most uniformly and finely disseminated than from austenite in which the carbon was not uniformly distributed.

Increasing T_{max} . (above A_{c3}) produces a large-grained austenite, to the grain boundaries of which the proeutectoid ferrite of hypoeutectoid steels is rejected during cooling; and the segregation thus formed is progressively more detrimental to the physical properties of the slowly cooled steel as the carbon content of the steel decreases.

Increasing the time of holding at temperatures above A_{c3} beyond a certain undetermined limit (probably between 10 and 30 minutes for the steel used) has a detrimental effect on the physical properties of the steel when cooled slowly enough to produce pearlite. This is attributed to a slackening in diffusion and a continuance of grain growth with time at a given temperature.

All physical properties of hypoeutectoid steels are increased with increase in cooling rate from above A_{c3} , provided the resultant steel is pearlitic. This is attributed to the fact that the rapidly cooled steels are finer grained, regardless of the temperatures above A_{c3} from which they cool.

G. C. Priestler and O. E. Harder, *Effect of Temperature on the Mechanical and Microscopic Properties of Steel* (Chemical and Metallurgical Engineering, January 17, 1923, vol. 28, pp. 111-114). The investigation had for its purpose a study of the mechanical properties of steels at elevated temperatures, the properties of these same steels at ordinary temperature after having been heated to various drawing temperatures, and, finally, the correlation of these properties with the microstructure. Plain carbon steel with 0.16 carbon, when tested at temperatures ranging from 20 to 600° C., shows a maximum in the maximum stress, yield point, and proportional limit curves at about 300° C.; however, these values do not exceed the corresponding values at 20° C. It shows a minimum in the reduction of area curve at approximately this same temperature, with a less pronounced minimum in the elongation curve. These changes in the physical

properties are due to the temperature at which the test is made, and are not the result of the steel having been drawn or tempered at a certain temperature. Above 300°C . the minimum stress, yield point, and proportional limit decrease almost as a straight-line function of the temperature at which the test is made. And the effect on the maximum stress is the most pronounced. There is a corresponding increase in the reduction of area and elongation, but the elongation is approximately constant above 400°C . The impact toughness increases with the drawing temperatures. The results of the impact tensile tests show a slight decrease in the tensile strength, reduction of area and elongation for specimens drawn at 100°C . At higher drawing temperatures these values increase with increase in the drawing temperature. Microscopic examination shows changes in the micro-structure which correspond to the changes in the mechanical properties at the higher temperatures (400° to 600°C .), but do not seem to throw any light on maximum and minimum points in the curves for tests at 300°C .

H. R. A. Mallock, *Effect of Temperature on Some of the Properties of Steel* (Proceedings of the Royal Society, April 1923, vol. 103-A, pp. 1-7). In studying the effect of temperature on the elastic coefficient of solids, some experiments were made with the object of measuring at high temperatures the variation of the rigidities of iron and steel. In making his first observations on the phenomena of recalescence in 1873-4, the author noticed that the peculiar feature of re-extension and recalescence occurred at a higher temperature for iron than for steel, and although it was evident from the diagrams that the contraction in terms of time followed the usual exponential law, both above and below the temperature of recalescence, it was also evident that the coefficient of the time in the exponent was different in the two cases. This indicated a change either of specific heat, of temperature expansion coefficient, or both, and the present series of experiments endeavour to prove how far either change was responsible for the observed effect. An apparatus was devised for continuously recording the period of torsional oscillation, the temperature, and the length of a wire while cooling. The chief results noted were a small and gradual change in the rigidity of the steel up to a dull red heat and its rapid decrease above the critical temperature, and that the rate of expansion shows no sudden change at that temperature, but that the expansion itself from 0° to 1000°C . can be fairly represented by a straight line. The constancy of the rate of expansion above and below the critical temperature proves that the difference in the exponential coefficient in the cooling curves must be due to a change of the specific heat of steel while passing from the cool to the allotropic hot form.

M. Sauvageot and H. Delmas, *The Tempering of Soft Steel at Very High Temperatures* (Comptes Rendus, April 23, 1923). A mild steel containing 0.09 per cent. carbon was quenched in water from

temperatures ranging from 950° to 1450° C. The elastic limit, tensile strength, and hardness increased rapidly as the temperature of quenching rose.

R. Krieger, *Some Considerations on the Testing of Cast Steel* (Stahl und Eisen, November 30, 1922, vol. 42, pp. 1769-1773). The prescribed rules for testing cast shell steel are criticised. The specification for cast steel for shells required a minimum tensile strength of 36 kilogrammes per square millimetre and a maximum elongation of 2 per cent. The composition of the material was specified as 0.49 per cent. carbon and 1.16 per cent. manganese, which corresponded, if the steel was otherwise of good quality, to a tensile strength of about 70 kilogrammes per square millimetre. The difficulty was to keep the elongation down to the maximum permissible, with the result that much bad material was passed as satisfactory, while good material was often rejected.

R. H. Greaves, *Effect of Overstrain on the Elastic Properties of Steel* (Research Department, Woolwich: R.D. Report, No. 45, 1920, 17 pp.).

R. H. Greaves, *Recovery of Elasticity by Iron and Steel after Overstrain* (Research Department, Woolwich: R.D. Report, No. 54, 1922, 25 pp.). The material investigated consisted of samples of wrought iron, mild steel, and crucible steel, which had formed part of the material used by Sir Alexander Kennedy in a research made between 1886 and 1890 on the elastic properties as affected by overstrain, and placed by him at the disposal of the Research Department, a sample of mild steel, and one of an oil-hardened and tempered nickel-chromium steel. The treatments consisted of the application of various overstraining loads, either momentarily or continuously, followed by periods of rest. It was found that the rate of recovery of elasticity varies greatly with different steels, the harder steels in general recovering more slowly. The greater the degree of overstrain the longer is the time required to bring about recovery at a given temperature, or the higher the temperature required to bring about recovery in a given time. In the case of the harder steels, recovery at atmospheric temperature is very slow. The effect of thirty years' rest at atmospheric temperature is about the same as holding for one hour at 100° C., and considerably less than the effect of holding one hour at 125°. After complete recovery of elasticity, no further change occurs in the position of the elastic limit on ageing for thirty years. When the overstraining load is applied momentarily the new elastic limit after recovery is less than the overstraining load. When the application of the load is prolonged the elastic limit after recovery will exceed any load previously applied to the specimen.

Z. Jeffries and R. S. Archer, *Overstrain, Internal Stresses and Creep* (Chemical and Metallurgical Engineering, October 25, 1922, vol. 27, pp. 833-837). Iron is hardened much more by working in a blue heat range than at certain lower temperatures. This behaviour may be

a general property of metals, and has been observed in nickel and certain alloys. These phenomena and the results of overstrain are all due to the rapid acquisition of increased strength on slip planes. The elastic limit of iron is lowered sometimes to 0 by cold working, but is restored by ageing or heating at low temperatures to a value which may be much higher than its original value.

J. W. Landon, *Change of Density of Iron due to Overstrain*. (This Journal, p. 455.)

L. Guillet, *Products which have been Cold-Worked by Tensional Stresses and by Drawing* (Revue de Métallurgie, Mémoires, January 1923, vol. 20, pp. 63–66). The most important effect of cold working is the increase in the elastic limit of the metal and the conference of greater homogeneity, which makes the elastic limit and the breaking stress correspond more closely. On the other hand, one of the reasons for mistrusting cold-worked products arises from the fact that drawing, which is almost the only method industrially employed for cold working, is applied somewhat violently. Cold working, moreover, cannot satisfactorily be applied for the production of many important sections. The results of a number of experiments on dead-soft, soft, semi-hard, and hard steels are given.

F. Körber, *The Mechanical Properties and Structure of Critically Cold-Worked and Annealed Mild Steel* (Mitteilungen a.d. Kaiser-Wilhelm Institut für Eisenforschung, 1922, vol. 4, pp. 31–48). The experiments described form the continuation of an investigation made during the war with the object of reducing by suitable treatment the resistance of commercially pure low-carbon steel to mechanical deformation, and to make it approximate in this respect to electrolytic iron, which on account of its soft yielding quality, was used for many purposes, and especially for driving-bands of shells, as a substitute for copper. The difficulty was that a supply of electrolytic iron was not forthcoming in sufficient quantity. Attempts to soften commercially pure mild steel by the complete removal of impurities were unsuccessful, and the only other means of bringing about a low resistance to deformation was to produce by suitable treatment a change in the grain size of the material so delivered. For the present experiments steel bars were used of 20 millimetres diameter and 300 millimetres long, and of the following composition: Carbon, 0.08; silicon, 0.02; manganese, 0.07; phosphorus, 0.01; sulphur, 0.002; copper, 0.04 per cent. By means of cold working the length of the bars was increased by 11.1 per cent. and the area of cross-section decreased by 10 per cent. The bars were then annealed at various temperatures and for different periods, the following being the main results. The critical annealing range, within which the marked grain growth of critically cold-worked mild steel occurs, lies between the temperature of 650° and the Ac₃ point. In consequence of the critical cold-working and annealing a great diminution in the resistance to deformation is noticeable. This is indicated by a lowering of the limit of elasticity to about

one-quarter of its original value and of the limit of flow to about one-half. The tensile strength and hardness are reduced in a less proportion, while the elongation shows little change; the pearlite balls together forming separate pearlite islands. Steel that has been rendered coarsely crystalline by critical cold-working and annealing shows great brittleness under the notched-bar test, but under a static or dynamic test on plain bars it shows about the same capacity for deformation as normalised mild steel.

Z. Jeffries and R. S. Archer, *The Properties of Cold-Worked Metals* (Chemical and Metallurgical Engineering, November 1, 1922, vol. 27, pp. 882-889). Hardness and strength of a metal increase with the amount of reduction by cold-work until internal failure is produced. Plasticity of a metal decreases as the amount of cold-work increases. With change in temperature of the test, the properties of a cold-worked metal follow those of annealed metal, any discontinuities in the properties of annealed metal being reflected in those of cold-worked metal. The effect of a given deformation is greater the lower the temperature at which it is effected, except that in some metals abnormally large effects are produced in a certain region of temperature corresponding with the blue heat in iron. Elongation of a cold-worked metal increases with respect to the elongation of annealed metal, as the temperature of test decreases below the working temperature, reaching a maximum value after which further decrease in temperature produces a rapid decrease in elongation. Elongation of a cold-worked material decreases with respect to the elongation of annealed metal as the temperature of test is raised above the working temperature until the recrystallisation temperature is reached, when elongation is increased by annealing. Temperatures of maximum elongation are different for various metals. For any given metal the temperature of maximum elongation is lower the greater the amount of cold-work, and is in general lower in cold-worked metal than in annealed metal.

J. Czochralski, *The Principles underlying the Cold-working Effect* (Zeitschrift für Metallkunde, January 1923, vol. 15, pp. 7-16). From the results of cold-working operations performed in various axial directions on single crystals of copper and aluminium, conclusions are drawn with regard to the phenomena of the increase of strength of metals produced by cold-working. This has its foundation in the properties and geometry of the space lattice.

F. Sauerwald, *The Essential Factors in Cold Working and Recrystallisation, according to Results of Experiments on Metallic Bodies in the Form of Powder* (Zeitschrift für Elektrochemie, February 1, 1923, vol. 29, pp. 79-85).

T. F. Russell, *The Potential Energy of Cold-worked Steel*. (This Journal, p. 497.)

J. Stead, *The Cold Working of Steel with Reference to the Tensile Test*. (This Journal, p. 377.)

A. Lundgren, *Effect of Cold Working and subsequent Annealing on*

the Tensile Strength of Iron and Steel (Jernkontorets Annaler, 1922, vol. 77, pp. 499-513).

C. W. Yearsley, *A Physico-Chemical Interpretation of the Effects of Stress upon Metals* (Journal of the Birmingham Metallurgical Society, vol. 8, No. 4, pp. 129-143).

C. H. Desch, *Brittleness and Fatigue in Metals* (Transactions of Institution of Engineers and Shipbuilders in Scotland, August 1922, vol. 65, pp. 21-35). The author discusses the requirements in testing metals used in high-speed engines, and especially in aeroplane engines in which weight is reduced to a minimum and the stresses are intense and alternating. A perfectly satisfactory method of testing has not yet been found, there being some forms of brittleness which are not revealed by all the methods used in mechanical testing laboratories. The difficulty of determining the elastic limit is referred to, and the importance of the properties of single crystals is made clear. The rate at which stress is applied is also a factor of great importance. Various attempts to arrive at some means of determining fatigue limits by rapid methods are described, and it is suggested that when it becomes possible to calculate the actual values of the resistance to tensile stress and shear, measured between the adjoining planes of the space lattice of the atoms, the testing of metals will have been placed on a scientific basis.

C. F. Jenkin, *Fatigue in Metals* (Paper read before Royal Aeronautical Society, December 7, 1922: Engineer, December 8, 1922, vol. 134, pp. 612-614). By means of a simple form of model, various phenomena in connection with the fatigue of metals are demonstrated and explained. Experiments throwing a new light on the conditions producing fatigue are described, and it is shown how the fatigue limit of a material can be lowered by breaking down all the crystal adhesions, and is restored by keeping it at the temperature of boiling water for two hours; this treatment produces healing of the crystals and restores their adhesion, raising the fatigue limit to 21 per cent. above its original value, after lowering it to 25 per cent. below that value.

T. Robson, *Determination of the Fatigue-Resisting Capacity of Steel under Alternating Stress* (Engineering, January 19, 1923, vol. 115, pp. 67-68). An illustrated description is given of a machine of the ordinary Wöhler cantilever type in use in the testing department of the North Eastern Railway for performing alternating stress tests on materials subject to such stresses in service. The appliance for measuring the deflection will give readings up to one five-thousandth of an inch at the end of the test piece.

H. F. Moore and T. M. Jasper, *An Investigation of the Fatigue of Metals* (Illinois University Engineering Experiment Station, 1922, Bulletin 136). This bulletin contains data on the fatigue phenomena of porous materials obtained since the publication of the former report (Bulletin No. 124). The results of the present investigation confirm the existence of an endurance limit for wrought-ferrous metals, the

endurance limit being defined as the unit stress below which a metal is capable of withstanding an indefinitely large number of reversals of stress.

H. F. Moore, J. B. Kommers, and T. M. Jasper, *Fatigue or Progressive Failure of Metals under Repeated Stress* (Proceedings of American Society for Testing Materials, 1922, vol. 22, Part 2, pp. 266-287). The apparatus and form of specimens for repeated stress tests are illustrated and described, with some discussion of the results of such tests.

P. Ludwik and R. Scheu, *Behaviour of Metals under Repeated Stress* (Zeitschrift des Vereines deutscher Ingenieure, February 10, 1923, vol. 67, pp. 122-126). A report is published of a series of investigations made at the laboratory of the Technical High School, Vienna. Alternating stress tests were performed on mild steel specimens and other metals, and the relation between stress and number of alternations, and the influence of hardness and ductility, and of the mechanical and thermal treatment on the strength of material under duration test were studied. Diagrams of the deformation of fatigued material are shown and the cold-working effect on the crystal form and the changes of structure are also dealt with.

W. Müller and H. Leber, *Degree of Stress, Grain Size, and Temperature in Relation to Fatigue Phenomena* (Zeitschrift des Vereines deutscher Ingenieure, April 14, 1923, vol. 67, pp. 357-363). The article deals with the strength properties of steel as revealed by dynamic as compared with static tests.

H. L. Whittemore, *Résumé of Impact Testing of Materials, with Bibliography* (Proceedings of American Society for Testing Materials, 1922, vol. 22, Part 2, pp. 6-36). The paper gives a brief outline of the history of impact testing, with a lengthy bibliography of the literature on the subject.

D. J. McAdam, *Impact Tests of Metals* (Proceedings of American Society for Testing Materials, 1922, vol. 22, Part 2, pp. 37-54). A general review of the technology of impact testing, with some description of the various machines used for the purpose.

T. D. Lynch, *Review of the Work on Impact Testing done by the British Engineering Standards Association* (Proceedings of American Society for Testing Materials, 1922, vol. 22, Part 2, pp. 100-103).

C. E. Margerum, *Measurement of Pressures Caused by Impact* (Proceedings of American Society for Testing Materials, 1922, vol. 22, Part 2, pp. 104-116). The time-space method, the measurement of cushioned impacts by the time-space method, the deflection method, and the deformation method are discussed; an apparatus for recording maximum pressure in the Charpy impact test is also illustrated and described.

A. Elmendorf, *Measuring Forces in Impact* (Proceedings of American Society for Testing Materials, 1922, vol. 22, Part 2, pp. 117-123).

H. F. Moore, *Measurement of the Force of Impact by Means of the Elastic Stretch of a Steel Bar* (Proceedings of American Society for Testing Materials, 1922, vol. 22, Part 2, pp. 124-127).

F. C. Langenberg and N. Richardson, *Significance of the Impact Test* (Proceedings of American Society for Testing Materials, 1922, vol. 22, Part 2, pp. 128-136).

F. C. Langenberg, *An Investigation of the Behaviour of Certain Steels under Impact at Different Temperatures* (Iron and Steel Institute: Carnegie Scholarship Memoirs, 1923, vol. 12, 34 pp.). The investigation was undertaken to determine the differences in the amount of energy absorbed in fracture by dynamic stress, or the differences in resistance to impact which are exhibited by certain steels when tested at different temperatures. Six steels were selected for the experiments, namely, a high, medium, and low carbon steel, a low carbon nickel-chromium, a medium carbon nickel-chromium, and a medium carbon nickel steel.

J. H. Andrew and R. Hay, *The Izod Impact Test* (Journal of the West of Scotland Iron and Steel Institute, Session 1922-1923, vol. 30, Part 4, pp. 48-53).

H. Pommerenke, *Brittleness of Steel and Impact Tests on Notched Bars* (Revue de Métallurgie, Mémoires, 1922, vol. 19, pp. 741-747).

N. B. Pilling, *Low Temperature Brittleness in Silicon Steels* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). The author has investigated the cause of brittleness in thin-rolled silicon steel sheets, as used in transformer construction. When the silicon content exceeds 4.2 per cent. the sheet is too brittle for satisfactory shaping by punching or similar operations. When such a brittle sheet is sheared, it frequently breaks along a haphazard path in advance of the cutting tool. The results of the investigation show that this brittleness is an inherent property of iron modified by the silicon. Temporary ductility may be obtained by carrying out cutting or shaping operations at temperatures slightly above atmospheric, the temperature depending on the composition of the steel. The brittleness is only slightly modified by heat treatment.

H. Moore, *The Ball Hardness Test* (Paper read before the Birmingham Metallurgical Society, January 11, 1923). The author deals with some of the less familiar aspects of the Brinell hardness test, and indicates some directions in which its usefulness might be extended. The laws expressing the effect of variation in load and in diameter of ball on the hardness number are discussed, and a description is given of a method for indicating the capacity of a material for hardening by cold work. The application of these laws in the employment of small balls and loads for the determination of the hardness of thin specimens is shown.

R. Genders, *The Scleroscope Hardness Test: A New Form of Magnifier Hammer* (Journal of the Institute of Metals, 1923, No. 1, pp. 445-466). The Shore scleroscope as at first devised did not prove sufficiently sensitive for performing hardness tests, and a drop hammer was designed in substitution for the ball. The nose of the hammer as now supplied is a truncated cone, slightly rounded at the apex. Due

to slight variations in the contour of the striking portion of the hammer, lack of agreement was found in readings from different scleroscopes, and a new form of magnifier hammer has been devised in which constant contour of the nose is ensured by employing a hardened steel ball.

C. A. Edwards and C. R. Austin, *A Contribution to the Study of Hardness*. (This Journal, p. 323.)

H. O'Neill, *Variation of Brinell Hardness Number with Testing Load*. (This Journal, p. 343.)

Symposium on Hardness Testing (Transactions of the American Society for Steel Treating, February 1923, vol. 3, pp. 480-501). Two papers were presented. The first, by H. P. Hollnagel, "*Significance of Hardness Testing*," draws attention to the diversity of opinions regarding the definition of hardness, and outlines the methods of hardness testing. The second paper, by H. M. German, "*Testing of Metals for Hardness*," classifies the types of hardness-testing machines.

F. Körber and I. B. Simonsen, *Dynamic Hardness Testing by the Differential Method* (Mitteilungen a.d. Kaiser-Wilhelm Institut für Eisenforschung, 1922, vol. 4, pp. 61-66). A method is described by which the range of hardness measurement with a portable Brinell differential meter for making dynamic hardness tests can be considerably increased. The method consists in a modification of the mode of calculating the hardness from the dimensions of the impression.

Pendulum Hardness Tester (Iron and Coal Trades Review, April 20, 1923, vol. 106, pp. 564-565). The hardness tester described has been introduced by E. G. Herbert Ltd., Manchester, and is extremely simple in design. A ball, of ruby or of steel, 1 millimetre in diameter, is held in a chuck in the centre of the instrument, and six screwed weights are provided whereby the position of the centre of gravity may be adjusted to coincide with the centre of the ball. Immediately above the ball is a graduated weight mounted on a screw. By raising and lowering the weight the centre of gravity can be brought to a predetermined distance above or below the centre of the ball. The instrument constitutes a pendulum oscillating about its central position, the time of oscillation being greater as the length of the pendulum (the distance between the centre of gravity and the centre of the ball) is less.

5000 Kilogramme Hardness Tester with Accessories (American Machinist, European Edition, May 5, 1923, vol. 58, pp. 69-70-E.). Particulars are given of the Amsler hardness-testing machine. A number of accessories have been designed so that the machine can be used for bulge, compression, transverse, shearing, and tension tests, besides the Brinell hardness test.

H. A. Holz, *Elastic Column Dynamometer for Hardness Testing* (Chemical and Metallurgical Engineering, February 7, 1923, vol. 28, pp. 269-270). The elastic column dynamometer described imposes a load by a train of gears and screws, and can be operated in any position and at any range. It is designed by A. J. Amsler.

The Brunton Torsion Machine (Iron and Coal Trades Review, December 1, 1922, vol. 105, p. 813). Brief particulars are given of the Brunton torsion machine, which is mechanically operated, and will test all sizes of wire from and below $1\frac{1}{4}$ inch diameter.

J. P. Newell, *Pantograph Method of Determining Rail Wear* (Engineering News-Record, August 24, 1922, vol. 89, pp. 310-312). In connection with the valuation of the Grand Trunk Railway of Canada a pantograph method of determining the wear of rails was used. The method, which gives results of considerable accuracy, is described.

H. M. Dudgeon, *Tramway Rail Corrugation as a Function of Rail Vibration* (Tramway and Railway World, February 15, 1923, vol. 53, pp. 65-69). The author shows that rail vibration has a controlling influence on the coefficient of friction between the wheel and the rail, and that this is an important factor in tramway rail corrugation.

Prevention of Corrugation (Tramway and Railway World, April 19, 1923, vol. 53, pp. 178-180). An account of some successful experiments carried out by the London County Council to ascertain the resistance to corrugation of rails treated with the Sandberg hardening process.

E. Schneider, *Comparative Determinations of the Hardness of Tool Steel of Different Compositions under Hot Conditions* (Revue de Métallurgie, Mémoires, 1922, vol. 19, pp. 676-680).

Report of the Lathe Tool Research Committee (Manchester Association of Engineers, 1922, p. 89). The report contains the results of an investigation on the heat treatment, on the influence of shape on the efficiency of the tool, and on the power consumed. The steels tested were plain carbon steels, with carbon ranging from 0.22 to 0.514 per cent., and a series of alloy steels containing carbon 0.65, chromium 2.97, tungsten 13.08, and vanadium 0.52 per cent. The research was carried out under the auspices of the Department of Scientific and Industrial Research.

H. J. French and J. Strauss, *Lathe Breakdown Tests of Some Modern High-Speed Steels* (United States Bureau of Standards, 1923, Technologic Paper, 228).

Bibliography of High-Speed Tool Steels (Transactions of the American Society for Steel Treating, October 1922, vol. 3, pp. 47-89). A very complete bibliography of the literature on the manufacture of high-speed steel covering the period 1900 to May, 1922.

R. P. Neville and J. R. Cain, *The Preparation of Iron-Carbon-Manganese Alloys and the Effects of Carbon and Manganese on the Mechanical Properties of Iron* (United States Bureau of Standards, 1922, Scientific Paper, 453). The authors describe the preparation and mechanical properties of an extensive series of very pure alloys of electrolytic iron, carbon and manganese. (See also last volume of this Journal, 1922, No. 2, p. 400).

H. S. Rawdon and F. Sillers, jun., *Effect of Manganese on Carbon*

Steels (Iron Age, November 23, 1922, vol. 110, pp. 1356-1361). The authors have made a study of the microstructure of a comprehensive series of the iron-carbon-manganese alloys. One hundred and two alloys with the carbon varying from 0 to 1.60 per cent. and manganese 0 to 2 per cent. were used in the investigation. The effect of manganese as observed in annealed alloys is to confer upon the pearlite a very fine grained or sorbitic structure, even after slow cooling. The relative amount of pearlite present is considerably greater in the alloys of high manganese content than in corresponding ones low in this element. A pronounced increase in Brinell hardness of the annealed alloys accompanies the change in structure produced by the addition of manganese. The addition of manganese causes a shift in the eutectoid ratio toward lower carbon content. 1 per cent. of manganese lowers it to approximately 0.78 per cent. carbon. In the normalised alloys, a pronounced decrease in grain size was found in those of higher manganese content, in addition to the structural effects mentioned above. In the annealed specimens no noticeable difference in grain size was detected for high and low manganese contents in alloys of any given carbon content. The well-known effect of manganese in lowering the transformation temperatures will account in part for the observed structural changes. It appears also that manganese renders steel more "sluggish" and less responsive to structural changes than many of the other elements which produce a similar lowering of the critical temperature. While the results of the structural examination will not warrant any definite conclusions concerning the use of manganese as a strengthening element in steel, the results obtained strongly support previous recommendations concerning the advantages to be gained from the use of higher manganese, particularly in low and medium carbon steels.

G. K. Burgess, *The Study of Steels for Engineering Structures* (Paper read before the American Society of Civil Engineers, January 19, 1923; Iron Age, January 25, 1923, vol. 111, pp. 281, 320-321; Iron Trade Review, February 8, 15, 1923, vol. 72, pp. 443-445, 508-510). The author reviews the developments in the use of alloy steels for structural purposes. The use of nickel steel, nickel-chrome steel and silicon steel for bridges, and the possibilities of the use of copper steel are dealt with. There are possible uses of heat-treated steels in engineering structures, and such steels have been introduced to a limited extent as in lattices and auxiliary parts.

P. Chevenard, *Nickel Alloys which Retain their Tensile Strength at High Temperatures* (Comptes Rendus, September 25, 1922, vol. 175, pp. 486-489). Most steels and steel alloys when heated above 500° C. become viscous under a load of a few kilogrammes per square millimetre. Experiments showed that a nickel-chrome steel retains its rigidity above this temperature better than plain carbon steels, and that still better results were obtained from other alloys of nickel and chromium; the material which best preserved its strength at high temperatures

was an alloy of nickel with about 9 per cent. of chromium and 6 per cent. of tungsten.

C. E. Guillaume, *The Metals Invar and Elinvar: their Properties and Applications* (Revue de l'Industrie Minérale, Mémoires, October 15, 1922, pp. 545-572). A history of the discovery of these nickel-steel alloys, and an account of their properties and uses is given. Researches in this direction were stimulated by the need for finding some substitute for platinum in national and other standards of length, so that they could be distributed economically to various metrological and other physical laboratories. These researches led to the discovery of the two groups of nickel steel, those containing less than 30 per cent. of nickel, and a second group, containing from 20 per cent. of nickel up to 100 per cent. Although these groups overlap, they are broadly recognisable as reversible and irreversible in regard to their magnetic properties, but commercially only the first group, the reversible alloys, are of industrial interest. The influence of manganese, carbon, chromium and copper on the two typical alloys of the reversible group, invar, and the new elinvar, are described. These alloys, particularly elinvar, possess extraordinary low dilatations. They serve, in magnetic appliances, to record magnetic changes. They are used as filaments in incandescent lamps, in the construction of metronomes, and wherever compensation is ordinarily introduced to meet the variational dilatations of ordinary metals in sensitive instruments, clocks and watches.

D. Hanson and J. R. Freeman, *The Constitution of the Alloys of Iron and Nickel*. (This Journal, p. 301.)

C. R. Austin, *Some Mechanical Properties of a Series of Chromium Steels*. (This Journal, p. 419.)

J. A. Jones, *The Properties of Some Chromium Steels* (Research Department, Woolwich, R.D. Report No. 51, 1922, 19 pp.). The thermal critical ranges, microstructures and mechanical properties of a series of crucible steels containing about 0.4 per cent. carbon with 0 to 3 per cent. chromium have been determined. No new conclusions are reached, but the experiments illustrate in a fairly comprehensive manner the effect of moderate quantities of chromium on the properties of a structural steel.

J. A. Jones, *The Properties of Some Nickel-Chromium Steels* (Research Department, Woolwich, R.D. Report, No. 55, 1922, 51 pp.). The thermal critical ranges, microstructure, and mechanical properties of a number of nickel-chromium steels and one nickel-chromium-molybdenum steel have been investigated, and a comparison is made with the properties of steels treated in the mass. The results are fully set forth in tables and illustrated with diagrams and micrographs.

H. B. Pulsifer and O. V. Greene, *Structure of Chromium-Nickel Steel* (Chemical and Metallurgical Engineering, February 21, 1923, vol. 28, pp. 354-356). The structures of a chromium-nickel steel (carbon, 0.38; chromium, 1.08; nickel, 1.87 per cent.) and a

chromium-molybdenum steel (carbon, 0.46; chromium, 1.07, and molybdenum 0.35 per cent.) were studied. Both steels were normalised by heating to 1600° F. during sixteen hours, soaking eight hours, and slow cooling. A series of photomicrographs fail to show any change in structure in quenched chromium-nickel steel after various draws. Since the physical and chemical properties have changed very greatly, it is inferred that the atomic readjustments caused by the heating are submicroscopic. In the chromium-molybdenum steel there is much evidence of the formation of troostite. Two specimens, drawn at 1300° F. after quenching in oil and water respectively, show considerable amounts of a second component. This etches out dark in the picric acid solution, its granules are extremely fine, and it likely corresponds to the troostite of the simple carbon series. Precautions necessary in etching and photography are outlined.

F. G. Hibbard, *Chrome-Nickel Steel in Track Work* (Iron Age, March 15, 1923, vol. 111, pp. 753-757). The author gives an account of the use of chrome-nickel steel by the Milwaukee Electric Railway and Light Co., for special track work, such as crossings, frogs and switch pieces. The steel used is of the following composition: carbon, 0.30 to 0.40; manganese, 0.90 to 1.10; phosphorus, not over 0.03; sulphur, not over 0.04; silicon, 0.15 to 0.20; chromium, 0.55 to 0.65, and nickel, 2.20 to 2.40 per cent. The method of heat-treating is described. While the ordinary tensile tests can be met by the low chromium-nickel steel, longer life and better wearing qualities may be expected by the use of a higher percentage of these alloys. With reference to the wearing qualities it is found that chrome-nickel steel does not flow under compressive stresses as does manganese steel. The chrome-nickel steel can also be successfully welded and machined.

L. J. Barton, *Heat-Treatment of Electric Carbon and Alloy Steels* (Forging and Heat-Treating, February 1923, vol. 9, pp. 102-105). The characteristics of plain carbon steels and alloy steels containing nickel, chromium, molybdenum, and vanadium are generally discussed, and the effect of various heat-treatments on the physical properties of these materials are described.

H. W. Gillett and E. L. Mack, *Experiments with Rare Metal Steels: Uranium, Boron, Titanium, Zirconium, Cerium, and Molybdenum* (Paper read before the American Electrochemical Society, May 1923). Of these elements used in heat-treated steels only molybdenum has a decided and beneficial effect. In the types of steel in which the other elements were used they were either of slight effect one way or the other, or decidedly harmful. Uranium probably has a slight strengthening effect, but similar results can be obtained by cheaper means. Boron and cerium are harmful. Titanium and zirconium have about as much effect as equal amounts of silicon.

P. A. Heller, *Uranium Alloys* (Metall und Erz, 1922, vol. 19, pp. 397-399). The preparation of alloys of uranium with nickel, iron, and aluminium is described.

J. S. Vanick, *The Mechanical Properties of Chrome-Vanadium Steels* (Transactions of the American Society for Steel Treating, November 1922, vol. 3, pp. 196-217). The investigation was undertaken for the purpose of obtaining information which would have a practical value in the design and construction of units in nitrogen-fixation equipment. The tensile properties, hardness and microscopic structure as affected by different heat-treatments were determined for a given series of chrome-vanadium steels. Three series of alloys were used, two in which either the chromium or vanadium content was varied while the carbon content was maintained as constant as possible, and a third series in which the chromium and vanadium contents were maintained constant while the carbon content was varied. It was found that the carbon series, containing from 0.15 to 1.20 per cent. carbon, 1.0 per cent. chromium and 0.18 per cent. vanadium, showed in the annealed state an improved tensile strength and a lowered ductility with an increase in carbon. With heat-treated specimens a similar effect occurs up to 0.60 carbon. Within the quenching temperature ranges investigated, the higher temperatures produce an improvement in tensile strength with an attendant loss in ductility. A rise in hardness accompanies the increased strength. The vanadium series, containing 0.3 to 0.4 per cent. carbon, 1.0 per cent. chromium and vanadium varying from 0 to 0.65 per cent., showed in the annealed state an improvement in toughness over corresponding carbon-chromium steels. The tensile strength is, however, but slightly affected. Heat-treatment develops an improvement in tensile strength and hardness. The ductility, as measured by the elongation, falls off rapidly when 0.3 vanadium is exceeded. The high reduction in area which is maintained over the entire group of vanadium steels, reveals, in the severe deformation over a localised section, the toughness or inherent ductility of the steel. In the chromium series, containing 0.30 to 0.40 per cent. carbon, 0.18 per cent. vanadium, and 0 to 14.5 per cent. chromium, the tensile and hardness properties after annealing remain quite uniform for increases in chromium up to 2 per cent. Chromium in excess of 2 per cent. increases the strength and hardness at the expense of the ductility. Heat-treatment develops the influence of the element and intensifies the effects which are indicated in the annealed specimens. An examination of the microstructure suggests the relation between the mechanical properties and the addition of different proportions of chromium, carbon, and vanadium. In the annealed specimens the effort of chromium and vanadium to form carbides results in the combination of a portion of these elements with the cementite. The concentration of chromium and vanadium into complex carbides causes a construction and disruption of the pearlitic areas, which in turn releases more ferrite and distributes the cementitic lamellæ more widely. The improvement in toughness of most of these steels is accounted for by the release of a portion of the ferrite and the co-incident reinforcement of the matrix by the distributed cementitic

lamellæ. In heat-treating, higher quenching temperatures than those applied to carbon steels are required to enforce the solution of the complex carbides, temperatures in excess of 1750° F. being necessary in the case of steels containing a large amount of chromium. A short bibliography is appended of the more important papers dealing with the properties and treatment of these steels.

R. H. Greaves, *German Gun Steels* (Research Department, Woolwich, R. D. Report, No. 57, 1923, 16 pp.). The steel of a number of German guns was examined, and the chemical composition and microstructure were determined. Whenever possible mechanical tests were made. In addition to the material from gun tubes, certain breech mechanism parts were examined. The results are given in tables and are fully discussed.

W. Mauksch, *Behaviour of Iron and Copper under Repeated Tensile Stress at Different Temperatures* (Mitteilungen a.d. Kaiser-Wilhelm Institut für Metallforschung, 1922, vol. 1, pp. 41-57). The amount of stress to which wrought iron can be subjected without failure decreases at 200° C. to about one half its value at room temperature but rises again to its original value at 300° C. In the case of copper the stress regularly decreases with the increase of temperature. The extension curve of test-pieces of iron and copper is a straight line, on the first time of applying the load. If unloaded and reloaded, the curve becomes concave to the axis of the abscissa, the curve of contraction on removal of the load being convex. Intersection of the curve at the axis does not take place, as there is always a small permanent increase after each unloading.

F. Johnson, *Influence of Iron on Copper and Copper Alloys* (Address to Birmingham Local Section of the Institute of Metals, October 10, 1922). Iron up to 0.5 per cent. deoxidises, toughens and strengthens copper, even in presence of arsenic. It has a strongly inimical influence on electrical conductivity. Copper is capable of holding about 3 per cent. of iron in solid solution. In certain copper alloys iron serves a useful purpose in improving strength and toughness, but in general the amount of iron should not exceed 1 per cent.

J. H. Whiteley and A. Braithwaite, *Some Observations on the Effect of Small Quantities of Tin in Steel*. (This Journal, p. 161.)

P. Oberhoffer and A. Gallaschik, *Iron Arsenic Alloys* (Stahl und Eisen, March 22, 1923, vol. 43, pp. 398-400). The iron-arsenic diagram as worked out by K. Friedrichs with the concentration range of 8.4 to 56.0 per cent. arsenic is reproduced, and the object of the present research is to investigate the more important portion of the diagram, from 0 to 8 per cent. arsenic, which has not yet been determined. A melt of about 70 grammes, consisting of electrolytic iron to which a 99.81 per cent. arsenic-iron alloy was added, was made in a Kryptol furnace in a current of nitrogen. The melt was allowed to solidify slowly and thereafter the average cooling rate was at 30° C. per second. The results of thermal and analytical examinations are plotted and micro-

graphs of the material with different percentages of arsenic are shown. With increasing percentages of arsenic the temperature of the magnetic change during cooling is very rapidly lowered (by about 80° at 0.5 per cent. arsenic) and then remains constant. The arsenic, however, exercises no influence on the point of magnetic change on heating.

B. D. Saklatwalla, *Inherent Effect of Alloying Elements in Steel* (Paper read before the American Electrochemical Society, May 7, 1923). The importance of the effect of alloying elements on the purely physical changes occurring among the constituents of steel is pointed out. Stress is laid on the study of the physical conditions and their alterations by alloying elements during the period of solidification. Attention is drawn to the importance of the effect of alloying elements on surface tension of the solidifying constituents. The idea is expressed of the possibility of co-ordination and equivalence among alloying elements based on the periodic system, especially referring to atomic volume.

J. M. Snodgrass and F. H. Guldner, *An Investigation of the Properties of Chilled Iron Car Wheels* (Illinois University, Engineering Experiment Station, 1922, Bulletin No. 134). This bulletin contains a report of an extension of the tests previously reported (Bulletin No. 129), and discusses the strains existing in wheels when subjected to the combined effect of mounting, static load and side-thrust pressures. It also deals with a series of tests made to determine the ultimate strength of the car-wheel flange.

J. M. Snodgrass and F. H. Guldner, *An Investigation of the Properties of Chilled Iron Car Wheels* (Illinois University, Engineering Experiment Station, 1923, Bulletin No. 135). This is the third and final report of the investigation of chilled wheels. It deals with strains due to brake application, the coefficient of friction between the wheel and the brake shoe, and with brake-shoe wear. Six chilled iron wheels and one forged steel wheel were used in the tests to determine the strains produced through the application of brakes under the normal conditions of speed, brake-shoe pressure, and length of run. In these tests data were secured for the determination of the coefficient of friction, the tangential pull, the work done by the brake-shoe on the wheel, and the weight of metal lost by the shoe. In addition, a series of tests were made to ascertain the coefficients of friction and the brake-shoe losses for a chilled iron and a steel wheel under similar conditions of brake-shoe pressure and speed, the shoe pressure ranging from 500 to 3000 lb. and the speed from 5 to 50 miles per hour. The determination of linear thermal expansion, for which a formula has been worked out, and the method of determining the temperatures in a rotating car wheel are described.

T. Swinden, *Collapse of Steel Plates* (Paper read before the Birmingham Metallurgical Society, February 8, 1923: Iron and Coal Trades Review, February 16, 1923, vol. 106, p. 220). The author has investigated the cause of failure of steel pans used for evaporating nitrate

solution. Experiments showed that a steel plate laid loosely on the bottom of the pan was not deteriorated, whilst similar plates cracked when riveted in the pan in the ordinary way. It was obvious, therefore, that stress was a necessary factor. The author suggests that since the action of nitrates was so distinctly different from that of chlorides, selective chemical action operated in producing season cracking in mild steel. He suggests that the embrittling action was due to an absorption in a state of solid solution of nitrogen or oxides of nitrogen from the nitrate solution, by the material forming the intercrystalline boundaries. Experience has shown that the crystal boundaries were more chemically active, and would more readily permit the passage of gases than the body of the crystal.

F. Sommer and F. Rapatz, *A Study of the Woody Fractures and Formation of Flakes in Steel* (Stahl und Eisen, November 16, 1922, vol. 42, pp. 1708-1712). On polishing and etching some small pieces cut from a steel billet showing a typical woody fracture the surfaces showed a large number of hair-cracks which passed through the whole structure of the material. A microscopic examination revealed numerous minute, hard, non-metallic inclusions, a few hundredths of a millimetre in size, and the explanation of the hair-cracks is that these, owing to their unyielding hardness, have an explosive effect on the surrounding steel when it is subjected to rolling or forging. These inclusions are considered to consist of particles of slag, and the more frequent occurrence of hair-cracks, and, consequently, of woody fracture in basic steel rather than in acid steel, is thought to be due to the fact that the basic slags are more flint-like in character, and the particles do not yield to rolling or forging operations; whereas acid slag particles are plastic and will draw out when the material is rolled. By taking special care in the working of the charge in basic furnaces, and by thoroughly deoxidising the bath and careful teeming of the metal, the trouble can be avoided. Flakes are distinct from the phenomenon of woody fracture, and are probably due to the effect of the residual products of deoxidation in causing ferrite to separate.

Specifications.—*British Standard Specification for Shafting for Marine Purposes* (British Engineering Standards Association, Report No. 3021, 1922).

British Malleable Specifications (Iron Trade Review, December 21, 1922, vol. 71, pp. 1701-1702). The new British specifications for malleable cast iron for Admiralty purposes, recently issued by the British Cast Iron Research Association, are published in full.

Structural Specifications (Iron Trade Review, April 5, 1923, vol. 72, pp. 1020-1023). The specifications adopted by the American Institute of Steel Construction for the design, construction, and erection of structural steel for buildings are given in full.

B. R. Dierfeld, *Steels for Automobile Construction* (Iron Age, November 9, 1922, vol. 110, pp. 1199-1203). Particulars are given of the

specifications of automobile steels used in the German and Swiss industries. The steels are classified according to their physical properties and carbon content. The specifications are based on those prepared by the Bayerische Motoren-Werke.

H. Chandler, *The Steel Requirements of the Automotive Industry* (Forging and Heat-Treating, November 1922, vol. 8, pp. 506-510). The article discusses generally the types of steel suitable for use in the manufacture of the more important parts of automobiles, the conditions of service, and the tests usually applied to determine the physical and mechanical properties of the material.

R. J. Allen, *Some Notes on the Inspection of Steel for Automobile Use* (Transactions of the American Society for Steel Treating, October 1922, vol. 3, pp. 43-46, 97). The only reliable way of obtaining information regarding the soundness of automobile parts is by means of the fracture test; this, while not made on the material actually used in the part, can, with the aid of a properly attached prolongation or extension, be carried so close to it that the possibility of variation is slight. These extensions are left undisturbed until after the parts have passed all stages of heat treatment and hardness inspection, when they are nicked, fractured off, and examined. The extensions are situated so that when fractured they expose a transverse section of the material. The value of physical tests depends upon the closeness with which they duplicate actual service conditions. The tensile test does not approximate very closely to the condition under which most parts are stressed. The Izod test also is not representative of the stresses met with in service. The Stanton test, with its fracture showing all the characteristics of a fatigue failure, duplicates these conditions closer than any other form of test tried.

Expansion of Steel.—W. Souder and P. Hidnert, *Thermal Expansion of a Few Steels* (U.S. Bureau of Standards, Scientific Paper 433, 1922, pp. 611-626). Experiments were made on twenty-eight samples of iron and steel of various compositions to determine their expansions over the range 25° to 945° C. The expansion of pure electrolytic iron melted *in vacuo* from 25° to 100° C. was found to be 12×10^{-6} . The average expansion of steels over the same range was 11.2×10^{-6} , and for the range 25° to 600° C. it was 14.2×10^{-6} . For ordinary steels heated above the critical range the coefficient of expansion was about 23×10^{-6} .

Magnetic Properties of Iron and Steel.—L. Fraichet, *Magnetisation and the Molecular Deformations of Steel on Tensile Stressing; Elastic Limit* (Revue de Métallurgie, Mémoires, January 1923, vol. 20, pp. 32-45). After restating the elementary principles of magnetisation and citing Weber's hypothesis, experiments are described having as their object the ascertainment of the magnetic variation of a steel bar placed in a magnetic field and subjected to tensional stresses. The apparatus

employed is described and expressions given for variations in magnetic flux and intensity. A number of diagrams are given illustrating the relations between the magnetic phenomena and the stresses undergone by the metal, and the conclusions arrived at are that a galvanometric record of the tests forms a valuable supplement to an ordinary stress-strain diagram.

P. Dejean, *The Magnetic Transformations of Iron and Steel* (Annales de Physique, September–October 1922, vol. 18, pp. 171–272). The history of research on the magnetic properties of iron and steel from the time of Gilbert onward is reviewed, after which the author describes a method for the automatic recording of induction temperature curves of a piece of steel in a constant magnetic field. With the aid of this method a series of steels with carbon ranging from 0.06 to 1.33 per cent. was studied. It is shown that the magnetic transformation of cementite takes place near 200° C. The critical points A1 and A2 appear in the induction-temperature curve for a specimen with a weak demagnetising field, the transformation at A2 being reversible but not at A1. An extra-mild steel was found to possess much hysteresis, which phenomenon disappeared on heating at 250°, and reappeared on cooling. In the case of a high-carbon steel quenched in water and reheated, the induction in constant field reached a maximum at about 300°, which corresponds to the change in the rate of expansion at that temperature. The magnetic properties of the steels in relation to the temperature are further fully discussed, and the paper concludes with an extensive bibliography.

H. Scott, *The Magnetic Change A2 in Silicon and Chromium Steels* (Chemical and Metallurgical Engineering, January 31, 1923, vol. 28, pp. 212–215). The transformation temperature of these alloy steels has been studied. The loss of magnetism cannot be relied upon to indicate the proper hardening temperature, since the carbon change-point is at a higher temperature than the magnetic change-point. From the thermal and magnetisation curves it is noted that A2–Ac2–Ar2 is a continuous change in the magnetisation of ferrite, reaching a maximum rate of change at 768° C. just below the temperature of total disappearance of magnetism. In carbon steels this change differs from that in pure iron in degree only, caused by the transformation of ferrite to austenite within its range. The critical temperatures Acl, Ar1, and Ac2 are modified as follows: Acl is raised 21° C. and Ar1 is raised 18° for each per cent. of silicon added up to at least 3 per cent., while Ac2 is lowered 21° C. for the same increment. Chromium raises Acl 11° C. and Ar1 6° C. for each per cent. addition up to about 7 per cent., above which they are stationary, but it lowers Ac2 only in the higher percentages.

J. F. Kayser, *Magnet Steels* (Electrician, May 25, 1923, vol. 90, pp. 557–558). The properties of magnet steels are discussed.

J. F. Kayser, *Cobalt Steels for Permanent Magnets* (Engineer, January 19, 26, 1923, vol. 135, pp. 57, 83–84). The addition of cobalt

to certain steels gives, when the samples are suitably hardened, an extremely high coercive force, and investigations have shown that the action of cobalt in this respect is remarkably uniform. Within fairly wide limits this action can be represented by the equation:

$$H_c = h \times (1 + kCo)$$

where h = the coercive force of the cobalt free base, Co the percentage of cobalt present, and H_c the coercive force of the cobalt alloy. The constant k depends upon the base alloy to which the cobalt is added, and for properly hardened samples reaches a maximum value with from 9 to 14 per cent. of chromium with about 1 per cent. of carbon. The application of cobalt steel magnets are described.

E. Gumlich, *A New Material for Permanent Magnets* (Elektrotechnische Zeitschrift, 1923, vol. 44, pp. 147-151). Data are presented concerning the properties of manganese-cobalt steels, and as showing the excellence of this material for use in the manufacture of permanent magnets. The alloy contains 4 to 5 per cent. manganese, and 30 to 35 per cent. cobalt, or 1.1 per cent. carbon, 3.5 per cent. manganese, 36 per cent. cobalt, and 4.8 per cent. chromium.

C. W. Drury, *Cobalt: Its Production and Uses* (Paper read before the American Electrochemical Society, May 1923). The production and uses of cobalt are outlined. It is used chiefly in the manufacture of stellite, and is one of the main constituents of permanent magnets.

J. Würschmidt, *The Magnetic Testing of Permanent Magnets* (Kruppsche Monatshefte, September 1922, vol. 3, pp. 205-209). The coercive force, true remanence and reversible permeability are measured for various kinds of steel, including one tungsten steel and eight cobalt steels of different composition, the analysis not being stated.

J. Coulson, *Effect of Nascent Hydrogen on Hard-Steel Magnets* (Physical Review, 1922, vol. 20, pp. 51-58). When magnets, after repeated heating and cooling, are exposed to the action of nascent hydrogen by being made cathodes in a sulphuric acid bath, the magnetic moment decreases, reaching in time a permanent value 5 to 20 per cent. less than the original moment. The ageing process is accelerated by raising the temperature of the electrolyte. After ageing in this way, hammering the magnets has practically no effect.

W. L. Cheney, *Measurement of Hysteresis Values from High Magnetising Forces* (United States Bureau of Standards, 1920, Scientific Paper 383). The author discusses an earlier attempt to measure hysteresis values by means of a modification of the "isthmus method," and the possible causes for discrepancies which appeared in the results as compared with those obtained on other types of apparatus. A new method of measuring the coercive force is described. Graphs are given which show the coercive forces and the residual inductions from successively higher maximum magnetising forces plotted against the latter as the independent variable up to a field of $H = 2500$ gauss.

J. Würschmidt, *The Initial Permeability of Various Kinds of*

Steel (Kruppsche Monatshefte, January 1923, vol. 4, pp. 1-6). The investigation was carried out on nickel steels with varying percentages of nickel. The initial permeability in all cases is greatly improved by annealing. It diminishes as the nickel content is increased from 1.5 to 26 per cent., a 26 per cent. nickel steel being almost non-magnetic. Beyond that point the permeability rises suddenly, and at 29.30 to 36 per cent. nickel it reaches an order of magnitude of 200 to 1600 in unannealed, and of 1000 to 2400 in annealed material. In general nickel steel follows the law that initial permeability increases as the quotient remanence/coercive force is greater.

Permeability of Malleable (Iron Trade Review, January 18, 1923, vol. 72, pp. 231-232). The high magnetic permeability and low hysteresis of malleable iron make this material suitable for frames of small motors and generators used on automobiles. The method of moulding a generator frame is illustrated and described.

T. Matsushita, *On the Magnetic Hardness of Quenched Steels* (Science Reports of the Tôhoku Imperial University, 1922, vol. 11, pp. 471-485). Curves of magnetic hardness relative to quenching temperature of carbon steels were determined. From these curves, a curve showing the relation between the quenching temperature for the maximum hardness and the carbon content was obtained, also a curve showing the relation between the maximum hardness and the carbon content. Below 850° the magnetic hardness of a high carbon steel quenched in oil is considerably less than that of the same steel quenched in water, but above 900° the hardness in the case of oil quenching is a little greater. The second quenching in oil produces a much greater hardness than the first quenching. The maximum hardness due to the second quenching in oil is almost the same as that in water quenching. The duration of time during which the quenching temperature is maintained does not affect the magnetic hardness obtained by quenching.

T. Matsushita, *On the Magnetic Hardness of Steels* (Proceedings of the Physical and Mathematical Society of Japan, 1921, Series 3, vol. 3, p. 62).

W. L. Cheney, *Preparation and Properties of Pure Iron Alloys ; II. Magnetic Properties of Iron-Carbon Alloys as Affected by Heat Treatment and Carbon Content* (United States Bureau of Standards, 1922, Scientific Paper 463). The author gives the results of a study of the effect of heat treatment and chemical composition on the magnetic properties of a series of unusually pure iron-carbon alloys ranging from pure iron to 1.6 per cent. carbon.

Non-Magnetic Cast Iron (Iron and Coal Trades Review, November 10, 1922, vol. 105, p. 689 ; Iron Age, January 18, 1923, vol. 111, p. 220). A non-magnetic cast iron, no-mag, is now being produced by Ferranti, Limited, for which it is claimed that, whilst cheaper than brass, gun-metal, and aluminium, it combines with its non-magnetic properties an increased electrical resistance, whilst it has a more complete freedom from hysteresis and eddy currents than any other material yet discovered.

This combination is shown in the following figures :

	Magnetic Permeability. Maximum.	Specific Resistance. Micro-ohms per Cm. Cube.
Ordinary cast iron	330·00	95·0
No-mag	1·03	140·0
Brass	1·00	7·5

By its use for end plates and shields for generators and motors the losses due to stray flux are reduced to a minimum, thus allowing distinct economies in design. For tensile and transverse strength no-mag follows the usual figures obtained with cast iron, but it has the advantages of greater toughness and malleability observable both in its high transverse deflection and in its resistance to shock. No-mag is similar in appearance to ordinary grey cast iron, and can be cast with the same facility and with the ordinary foundry equipment.

Microstructure, Crystallography, and Heat Treatment.—F. C. A. H. Lantsberry, *The Structure of Steels from the Standpoint of Colloidal Chemistry* (Journal of the Society of Chemical Industry, October 16, 1922, vol. 41, pp. 409–411–R). The changes produced in the structural constituents of steel may be explained as follows from the point of view of the colloid chemist: Cementite is regarded as the dispersed phase and ferrite as the dispersion medium. At high temperatures the degree of dispersion is great enough to produce the molecular solution austenite. As the material cools a temperature is reached at which the dispersed phase assumes the colloidal state and troostite is obtained. Troostite may be rightly regarded as a colloidal solution in which cementite is the dispersed phase. As the temperature falls, coagulation occurs and sorbite is produced. On still lower cooling pearlite is obtained, and the structure recalls very strongly the phenomenon of periodic precipitation. Colloidal chemistry therefore explains the reason for the peculiar laminated structure of pearlite, an explanation which will hold good for all other eutectics.

W. D. Bancroft, *Colloid Chemistry and Metallurgy* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1922). The author gives reasons for the rejection of Beilby's amorphous-film theory, and discusses the applications of colloid chemistry, and its relation to corrosion and ore flotation.

H. S. Rawdon and S. Epstein, *Structure of Martensitic Carbon Steels and Changes in Microstructure which Occur upon Tempering* (United States Bureau of Standards, 1922, Scientific Paper No. 452). A study of the changes in structure resulting upon tempering was made in a series of six carbon steels ranging from 0·07 to 1·12 per cent. carbon, quenched from temperatures varying from 750° to 1250° C. and tempered for different lengths of time at 100° to 650° C. Upon quenching, mar-

tensite is formed throughout each austenite crystal in a manner strictly analogous to the freezing of solid-solution alloys. A redistribution of carbon takes place and the conspicuous martensite plates are found to be distinctly lower in carbon than the "filling material" between the plates. The enrichment of the carbon in the "filling material" may be great enough in some steels as to allow small patches of austenite to persist after quenching. The changes in structure and in hardness which occur during tempering vary in character according to whether they take place above or below 250° C. Below this temperature the structural changes are relatively slight, and are best revealed in the higher carbon steels by an alkaline oxidising etching reagent or by immersion of a polished specimen in liquid air. At approximately 250° martensite and austenite, if present, undergo a transformation and the steel assumes a granular structural appearance and reacts vigorously toward dilute acid etching reagents. The granules, cementite particles, grow in size progressively as the tempering temperature above 250° is increased. Hardened steels, tempered by heating to temperatures below 250°, show a slight decrease in hardness; above this temperature the decrease is rapid.

H. S. Rawdon, *The Structure and Related Properties of Metals* (Transactions of the American Society for Steel Treating, March, 1923, vol. 3, pp. 649-679). The structural conditions of ferrous and non-ferrous alloys are discussed under the following headings. The structure of metals, the effects of the structure of alloys upon their properties, and the applications of the microscopy of metals. The paper is accompanied by numerous photomicrographs.

Structure and Related Properties of Metals (United States Bureau of Standards, 1922, Circular 113). Metallographic methods in use for revealing the structure of metals are described. The principles underlying the action of etching reagents are discussed and a list of reagents is given. The principal conditions which affect structure, chemical composition, application of heat, and mechanical working of the metal and the effect of structure upon the properties are discussed. The results of a large number of practical applications of the study of the structure of metals are given to show how an explanation of the "failure in service" of different types of metals and alloys may be reached by this means.

H. Scott, *The Effect of High-Temperature Quenching on the Microstructure of High Carbon Steels* (Transactions of the American Society for Steel Treating, March 1923, vol. 3, pp. 593-622). The conditions necessary to produce austenite at ordinary temperatures in a plain high carbon steel and some metallographic properties of this constituent are dealt with. In contradiction to current views, it is shown that austenite can be obtained with a very slow rate of cooling compared with that necessary to produce martensite in lower carbon steels, provided that over 1.5 per cent. carbon is dissolved. This was accomplished by heating a 1.78 per cent. carbon steel to nearly 1100° C. The

transformations in cooling steel are also considered with special reference to the effect of the rate of cooling and thermal stress on the distribution of martensite and troostite. It is shown that the periphery of cylinders during quenching is under tensional stress and this condition is favourable to the precipitation of troostite. Several significant aspects of the transformation of austenite to martensite are also discussed. The paper is accompanied by numerous photomicrographs.

T. Matsushita, *Some Investigations on the Quenching of Carbon Steels* (Paper read before the Iron and Steel Institute, May 1923). Incidental to the hardening of steel by quenching, there are several complicated phenomena, such as a spontaneous change of dimensions, quenching cracks, &c. In order to investigate experimentally the mechanism of hardening more in detail, and to find a method of avoiding quenching cracks if possible, an apparatus was constructed to indicate the internal change of steel during the process of hardening.

Summarising the results of these experiments with the quenching apparatus, the following conclusions can be drawn :

(1) The lowering of the A1 point in steel depends not only on the velocity of cooling, but also to a considerable degree on the carbon content. (2) In a high carbon steel the A1 transformation, when quenched in water, begins to take place at a temperature approaching that of the medium ; but, when quenched in oil, it takes place partially at a higher temperature. (3) In a low carbon-steel the transformation occurs at a somewhat higher temperature even with the water quenching. If this change takes place above 400° C. the steel is not hardened ; if it occurs between 300° and 400° the steel contains β martensite only, but below 300° it contains both α and β martensites. (4) There are two special points with regard to the lowering of transformation, 550° and 350° C. From the one to the other there is always an abrupt fall of the transformation point. (5) If the transformation of steel occurs above 550° the steel has a sorbitic or pearlitic structure, in the vicinity of 400° a troostitic, and below 350° a martensitic structure.

R. R. Moore and E. V. Schaal, *The Heat Treatment of Alloy Steels* (Forging and Heat-Treating, February 1923, vol. 9, pp. 113-121). The effect of heat treatment on the metallographic and physical characteristics of nickel-chrome, chrome-vanadium, and chrome-molybdenum steels is considered. The influence of various heat treatments on the tensile properties are summarised. The metallographic characteristics of the several steels are very similar ; all have a very fine structure and none show any evidence of troostite. In all quenched and drawn specimens the martensitic lines persist even in those drawn at 650° C., the only change occurring with the increase of drawing temperature being a gradual breaking up of the martensitic lines causing the formation of a granular or sorbitic structure.

S. S. Beliaeff, *Cored Structure in Quenched Manganese Steel* (Chemical and Metallurgical Engineering, November 29, 1922, vol. 27, p. 1086).

A sample of manganese steel which had been quenched in water from 1850° F. was etched with 3 per cent. nital. At 100 diameters it showed typical austenitic network structures, with inclusions of free mangani-ferous carbide. The same surface after repolishing and etched with Le Chatelier's reagent showed typical dendritic structure. A phcto-micrograph of the same specimen after double etching, but without repolishing between etching with the nital and the cupric reagent, shows the close connection between the grain boundaries of austenite and dendrites. This method of etching not only develops the grain of the alloy, but even reveals non-homogeneity in the grain itself, showing that each dendrite forms a crystal even after a quench from 1850° F.

H. D. Hibbard, *Temperatures at which Physical Changes Occur* (Iron Age, December 7, 1922, vol. 110, pp. 1492-1493). The list of temperatures given are chiefly those relating in some way to the production and heat treatment of steel. Differentiation is made between actual fusing points and the temperature causing sintering, softening, and fluidity.

Z. Jeffries and R. S. Archer, *Effect of Temperatures, Pressure, and Structure on Mechanical Properties of Metal* (Chemical and Metallurgical Engineering, October 11, 1922, vol. 27, pp. 747-751). Recrystallisa-tion, annealing, deformation and inclusions have a profound effect on size and shape of crystalline grains, and therefore on the properties of metals. The mechanical properties of single crystals have been studied. They suggest that single crystals may possess perfect elasticity. Failures of crystals under load always appear to take place along the so-called planes of weakness.

Z. Jeffries and R. S. Archer, *Mechanical Properties as Affected by Grain Size* (Chemical and Metallurgical Engineering, October 18, 1922, vol. 27, pp. 789-792). The authors indicate how variation in the average size of the crystalline grains comprising the metal may be expected to influence the mechanical properties of the aggregate.

L. E. Benson and F. C. Thompson, *Some Experiments on Grain-Growth in Iron and Steel*. (This Journal, p. 525.)

F. Wever, *Contribution to the Knowledge of the Carbides of Iron* (Mitteilungen a.d. Kaiser-Wilhelm Institut für Eisenforschung, 1922, vol. 4, pp. 67-80). A pure carbon steel, containing 0.86 per cent. carbon, was used for the purpose of developing a pearlitic carbide; a steel with 1.78 per cent. carbon was used for obtaining a carbide separated out for the most part from the γ mixed crystals; a Swedish charcoal pig iron with 3.3 per cent. carbon was used, from which 65 per cent. of the total carbide crystallised primarily out of the mass; and finally, with the object of obtaining as pure a carbide as possible, a small charge of pure electrolytic iron was melted with sugar charcoal, and was quenched as suddenly as possible from 2000° by pouring into a copper mould of 1 millimetre diameter. The lower end of the mould was connected with a powerful air-pump and the mould was plunged in cold water immediately after filling. By this means rods of 10 to

15 millimetres in length were obtained without further working, which showed a structure of cementite with very little ledeburite, and the total combined carbon amounted to 6.5 per cent., which was very nearly the theoretical proportion of carbon in primary cementite. The isolation of the pure carbides was carried out according to the method of Mylius, Förster, and Schöne (*Zeitschrift für anorganische Chemie*, 1896, vol. 13, p. 788), and after dissolving the iron the carbon content of the residues corresponded fairly accurately with the formula Fe_3C . With the aid of the X-ray analysis it was endeavoured to establish the following points: (1) Identity of the various kinds of cementite in the iron-carbon system; (2) the arrangement of atoms of the iron carbide; (3) the structural character of the magnetic change at 210° . The method of Debye and Scherrer was used to investigate the four kinds of cementite which had been isolated, and it was concluded that the several forms of cementite which are distinguishable in the iron-carbon system are identical. Secondly, that the iron carbide crystallises in a rhombic lattice, the quadratic formula for which is given, and the edge-length of the elementary ranges is calculated. The specific weight is accurately calculated at 7.82. Thirdly, by X-ray exposures of the crystals at temperatures above 210° it was observed that the magnetic change of the iron carbide is not connected with any change of the space-lattice type, in which respect the carbide exactly resembles pure iron and nickel. The quadratic formula and edge-length at 275°C. were recalculated and show but very slight modifications.

A. E. White, *Carbide Segregation in High-Speed Steel* (Transactions of the American Society for Steel Treating, January 1923, vol. 3, pp. 386-392). The factors governing the segregation of carbide in high-speed steel are discussed. Photomicrographs are given showing types of segregation.

C. H. Desch, F.R.S., and A. T. Roberts, *Some Properties of Steels containing Globular Cementite*. (This Journal, p. 249.)

L. Northcott, *A Note on Temper Carbon*. (This Journal, p. 491.)

F. C. Thompson and E. Whitehead, *Some Notes on the Etching Properties of the α and β Forms of Tri-Carbide of Iron* (Paper read before the Faraday Society, May 14, 1923). Experiments were described which were made with the object of producing a method by means of which the α and β forms of cementite could be differentiated under the microscope. A list of reagents is given which were found not to attack either form of the carbide. No acid reagent will darken cementite, and, with the exception of ammonium molybdate solution, no neutral solution was discovered which would do this. All the reagents which rapidly darken cementite are strongly alkaline, and a list of six of these is given. The best reagent found to possess potentialities in differentiating between the two forms of carbide was potassium copper cyanide.

R. G. Guthrie, *The Use of Various Kinds of Light in Metallography*

(Transactions of the American Society for Steel Treating, April 1923, vol. 3, pp. 710-719, 757). The physics of light and a few of the important laws which govern the action and behaviour of light and light-waves are discussed. The author also deals with the optics and mechanics of the metallurgical microscope, and various types of photographic plates for photomicrographic work. The use of ray filters and monochromatic light by the dispersion of white light into the different colours of the visible spectrum are reviewed. The use of polarised light in the photomicrography of opaque objects is discussed at length, and photomicrographs made by this method are included in the paper.

L. Guillet, *Recent Progress in Microscopic Metallography and Macrography* (Revue de Métallurgie, Mémoires, October 1922, vol. 19, pp. 614-625).

J. O. Arnold, *On the Correlation of the Chemical Constitutions of "True Steels" to their Micrographic Structures.* (This Journal, p. 213.)

F. W. Rowe, *The Metallography of Grey Cast Iron* (Metal Industry, December 15, 22, 1922, vol. 21, pp. 563-565, 583-584). The author outlines the fundamental principles and present trend of ideas regarding the metallographic nature of grey cast iron.

L. Loskiewicz, *The Time of Attack of Micrographic Reagents on Iron-Carbon Alloys* (Revue de Métallurgie, Mémoires, 1922, vol. 19, pp. 681-687).

C. Gresty, *The Examination and Photography of Cast Iron under the Microscope* (Foundry Trade Journal, April 5, 1923, vol. 27, pp. 273-279).

F. C. Thompson and E. Whitehead, *Changes in Iron and Steel at Temperatures below 280°* (Proceedings of the Royal Society, February 1923, vol. 102, A, pp. 587-599). This investigation consists in the measuring of the electrical resistivity and thermoelectric power of four materials of the following composition :

	O. Per Cent.	Si. Per Cent.	Mn. Per Cent.	S. Per Cent.	P. Per Cent.
Ingot iron	0.02	0.01	0.02	0.023	0.008
Mild steel	0.19	0.13	0.38	0.067	0.053
High carbon steel . .	0.99	0.47	0.39	0.069	0.09
White pig iron . . .	3.8	0.2	0.35	0.02	0.02

It is well known that carbide of iron, Fe_3C , has a change point at about 200° C., but there are also equally important changes in pure iron. It was found that iron shows abnormalities in the rates of increase of electrical resistance and electric potential against platinum at well-marked temperatures. Below 280° C. these temperatures are : 55°, 100°, 120°, 140°, 220°, and 245° C. Those at 120° and 220° C. are the most important. It is difficult to believe that these can be

of the nature of allotropic changes, and no explanation of them can be given at present. Under the same conditions carbide of iron possesses two well-marked points at 160° and 220° C. It is not clear whether these are distinct points or the ends of a single transformation range. When samples of iron and high carbon steel are quenched from 280° C. it is found that the electrical resistivities differ from those obtained by slow cooling. These values are not constant, but as the material tempers they gradually alter till after the lapse of some days the values practically coincide with those obtained by slow cooling.

A. Goffey and F. C. Thompson, *The Changes in Iron and Steel below 400° C.* (This Journal, p. 465.)

G. Borelius and F. Gunneson, *A New Type of Transition in Iron* (Annalen der Physik, 1922, vol. 67, pp. 227-235). The thermoelectromotive force of iron which had been heated to various temperatures and suddenly cooled was found to vary irregularly with the temperature reached in the heat treatment. The curves obtained indicate a series of transitions with all the forms of impure commercial iron studied. They are of an unknown type, and between 100° and 800° there are indications of seven transitions.

W. Schneider, *Influence of the Rate of Cooling on the Position of the Critical Points and the Structure of Carbon Steels* (Stahl und Eisen, October 19, 1922, vol. 42, pp. 1577-1584). Three carbon steels were examined, containing 0.30, 0.89, and 1.25 per cent. carbon respectively, and tables and curves are given showing how the points Ar_3 and Ar_1 are lowered as the rate of cooling is increased. The formation of martensite is accompanied by an evolution of heat. Heyn and Bauer showed that on heating quenched specimens and specimens annealed at 100° and 210° after quenching, a gradual evolution of heat took place, which reaches a maximum after annealing at 300° . Specimens annealed at 310° show the reverse condition, and the curve obtained indicates an absorption of heat.

K. Honda, *On the Nature of the A_1 Transformation in Carbon Steels* (Science Reports of the Tôhoku Imperial University, 1922, vol. 11, pp. 487-500). The author deals with the stepped A_1 transformation as viewed in the light of X-ray analysis.

J. A. Jones, *The A_{c1} Range in Alloy Steels.* (This Journal, p. 439.)

J. S. Vanick and W. W. Sveshnikoff, *Thermal Transformations in some Chrome-Vanadium Steels* (Transactions of the American Society for Steel Treating, February 1923, vol. 3, pp. 502-532). The effect upon the thermal transformations of varying the carbon, vanadium, and chromium contents of a typical chrome-vanadium steel is described. Increasing the carbon content from 0.16 to 1.16 per cent. lowers the transformations upon heating, which remain, however, some 10° to 30° C. above those for the corresponding alloy-free carbon steels. Increasing the vanadium content from 0.025 to 0.65 per cent. produces very small changes in the usual transformations. A_{c1} is slightly raised, passing A_{c2} at 0.18 per cent. vanadium and continuing its rise

at the rate of 1°C. for each 0.02 per cent. of vanadium. Ac_3 is lost in the slow progressive heat absorption above Ac_1 that marks the diffusion of the dissociated carbides which were initially a complex of iron, chromium, and vanadium. A complete solution of the alloying elements occurs at a temperature between 850 and 900°C. Increasing the chromium content from 0 to 21.0 per cent. produces a gradual rise in Ac_1 , effecting a junction with Ac_2 at 0.75 per cent. chromium. The rise continues, meeting Ac_2 at approximately 3.0 per cent. chromium and reaching a maximum at 7.7 per cent. chromium. The pronounced lowering of A_2 , when 7.7 per cent. chromium has been exceeded, shows the participation of a large portion of the excess to form an iron-chromium solution.

R. Vogel and G. Tammann, *The Ternary System Iron-Boron-Carbon* (Zeitschrift für anorganische Chemie, 1922, vol. 123, pp. 225-275). The disagreement in the results of previous investigators is found to be due to differences in the rate of cooling. Rapid cooling results in the separation of supersaturated mixed crystals. The authors have systematically studied the ternary system iron-boron-carbon. Equilibrium sets in so slowly in the system that the structure and properties of the alloys depend to a large extent on the preliminary heating. The limiting proportion of boron having an influence on the structure was found to be 0.02 per cent.

L. Grenet, *Modification of the Iron-Cementite Diagram* (Comptes Rendus, 1922, vol. 175, pp. 1067-1070). The author produces arguments to show that from the standpoint of the phase-rule diagram, the small quantity of impurities present in practically all irons is sufficient to bring about a clear differentiation between such irons and pure iron. An iron-cementite phase diagram based on his conclusions is shown.

N. T. Belaiew, *Heat Treatment of Steel* (The Russian Economist, 1922, vol. 2, Nos. 7-8, pp. 2498-2503). The author sets forth in clear and simple language the explanation of the iron-carbon diagram, and describes the phenomena occurring in a carbon steel in transition from the liquid to the solid state. The effect of heat treatment on the properties and structure is also dealt with.

S. Ozawa, *The Constitutional Diagram of the Iron-Carbon-Tungsten System* (Science Reports of the Tôhoku Imperial University, Sendai, 1922, vol. 11, pp. 333-350). The constitutional diagram of the iron-tungsten system was determined. By the addition of tungsten, the temperature of crystallisation of the iron-tungsten alloys is not so much affected as shown by Harkort (*Metallurgie*, 1907). It is dilatometrically ascertained that the A_3 point rises with the increase of tungsten, but its intensity gradually diminishes. The A_2 point, 790°C. , is not sensibly affected by the addition of tungsten. The investigation of the microstructure of the system leads to the same result as that of Honda and Murakami. There is only one compound existing between iron and tungsten, namely Fe_2W . From the magnetic

and microscopic investigation of the iron-carbon-tungsten systems it has been ascertained that the cementite and tungstide are mutually soluble to a certain concentration, and that in high carbon and tungsten steels these solid solutions decompose, giving out tungsten carbide. The ternary eutectic point has been determined to be 1065° , its composition being 15.0 per cent. of tungsten, 3.6 per cent. of carbon, and 81.4 per cent. of iron. The binary eutectics of austenite-cementite and austenite-tungstide, which meet at the ternary eutectic point above stated, were found by thermal analysis and from the microstructure.

K. Honda and T. Murakami, *The Structural Constitution of Iron-Carbon-Silicon Alloys*. (This Journal, p. 545.)

N. T. Belaiew, *Secondary Structures in Steel* (Chemical and Metallurgical Engineering, March 21, 1923, vol. 28, pp. 537-548). Giolitti holds that hypoeutectoid steels especially can be classified and their structure explained by the hypothesis that beta-iron assumes a granular, and alpha-iron a laminar, habit. The real point at issue between this view and that of the author, is whether a definite type of structure is more or less linked up with certain allotropic modifications of iron, or whether it is dependent on thermal treatment only. The author deals with two processes, the solidification process or "primary crystallisation" occurring in the mushy zone between the liquidus and solidus lines, and the process of granulation taking place in the austenitic zone. The former results in the formation of dendritic crystals or dendrites in every alloy. Transformation into gamma-iron involves recrystallisation into independent granules of austenite. Further change into alpha-iron causes three varieties of secondary structure, namely, network structure, Widmannstätten, and structure of large crystals. The author believes that by suitably altering the velocity of cooling through the granulation zone and the zone of secondary crystallisation, any one of the three types of structure can be produced. The type of structure depends in the first instance not on the chemical composition but on the conditions of cooling, and this brings into evidence the importance of crystallographic relation, not only in crystals and isolated grains, but in ingots and in every article manufactured of iron, steel, or any other metal or alloy.

E. J. Janitzky, *Characteristics of Air-Cooling Curves* (Transactions of the American Society for Steel Treating, December 1922, vol. 3, pp. 335-338). Cylindrical nickel specimens were cooled from different maximum temperatures in air. The size of the specimen was $\frac{7}{8}$ inch in diameter and $2\frac{1}{2}$ inches in length, with a hole drilled axially to half the length of the specimen for inserting the pyrometer couple. The couple was of nickel-chrome and connected to a time-temperature recorder, and with a duplex thermocouple usually used for thermal analysis. The heating was performed in a circular resistance electric furnace of $2\frac{1}{2}$ inches in diameter and 3 inches in length. The travelling speed of the paper was 0.22 inch per 3.5 minutes—0.22 inch represent-

ing the time interval spacing on the chart. It was found that the results of time-temperature curves of the air-cooling specimens lend themselves to simple calculation, and the data obtained are very useful in metallurgical problems. The salient point of the mathematical procedure is the adoption of a time constant by ascertaining the time required to half-way cool the range from its maximum temperature to zero in the Fahrenheit scale. Having the constant in linear length, and plotting it in multiples from zero on the X axis, which represents the time co-ordinate, one obtains, by projecting the units of the time constants as ordinates, until their intersection with the actual curve whose points coincide with temperature numerals t° derived by dividing the maximum temperature T° by the amount of time constants t or their fractions elapsed during cooling, plus one, or $t + 1$,

a formula which mathematically expressed will read $t^\circ = \frac{T^\circ}{t + 1}$, and the

actual time $T = tm$, m being the time of the time constant in minutes, seconds, or hours, t the amount of time constants elapsed. In respect to specimens where the curve is interrupted by a transformation point, two curves are dealt with, one representing the temperature drop from the maximum temperature to the start of the transformation, and the other setting in at the temperature after the heat evolution is completed to atmospheric temperature.

F. Wever and K. Apel, *Note on the Application of Thermal Analysis* (Mitteilungen a.d. Kaiser-Wilhelm Institut für Eisenforschung, 1922, vol. 4, pp. 87-94). A comparison is made of the results obtained by different methods of taking time-temperature curves and time-difference curves.

F. Wüst, A. Meuthen, and R. Durrer, *The Temperature Heat-Content Curves of the Technically Important Metals* (Forschungsarbeiten auf dem Gebiete des Ingenieurwesens, No. 204; Verein deutscher Ingenieure, 1918, 63 pp.). The mean specific heats and true specific heats of iron and a number of other metals, from 0° to 1600° C., have been calculated.

F. Wüst and R. Durrer, *The Temperature Heat-Content Curves of the More Important Alloys of Metals* (Forschungsarbeiten auf dem Gebiete des Ingenieurwesens, No. 241, 1922, 46 pp.) The work forms a continuation of the foregoing study, and deals with four non-ferrous alloys.

C. H. Desch, *The Metallurgical Applications of Physical Chemistry* (Transactions of the Chemical Society, February 1923, vol. 123, pp. 280-294).

R. Schenck, *The Importance of Physical Chemistry in the Metallurgy of Iron* (Stahl und Eisen, January 18, February 1, 1923, vol. 43, pp. 65-69, 153-159).

H. H. Lester, *Radiography of Metals at Watertown Arsenal* (Army Ordnance, vol. 3, pp. 210-215; Mechanical Engineering, April 1923,

vol. 45, p. 257; Chemical and Metallurgical Engineering, February 7, 1923, vol. 28, pp. 261-266). The results are given of an examination of steel castings by radiography. The limit of penetrability based on thirty minutes' exposure with apparatus commercially available is placed at approximately 3 inches of steel. The magnitude of a fault may be judged from the area and relative density of the image only within rather indefinite limits. For thickness of metal near the limit of penetrability a flaw approximately 2 per cent. of the thickness of the metal may be detected. Where the flaw is sufficiently large or sufficiently close to the film so that the pinhole effect is not important, the definition of the image remains sharp as long as the image is visually detectable in the negative. Properly developed radiographs indicate not only the presence of defects such as gas cavities, but even their exact dimensions. Where the linear dimension of the flaw, that is, the dimension parallel to the axis of the X-ray beam, is approximately equal to $1\frac{1}{2}$ per cent. of the total thickness of the metal in the region adjacent to the flaw, the image may be distinguished. For practical working conditions detectability may be placed at 2 per cent., which means that a cavity 0.05 inch diameter can be detected in metal 2.5 inches thick. To locate a cavity a stereoscope is used, and two exposures are made, 2.36 inches apart. After development the negatives are placed in a stereoscope, and when properly adjusted, the picture stands out in bold relief, the faults appearing in their proper place within the material, and the impression is given of looking at a transparent model of the casting.

Sir W. H. Bragg, *The Significance of Crystal Structure* (Transactions of the Chemical Society, December 1922, vol. 121, pp. 2766-2787).

R. W. G. Wyckoff, *A Survey of Existing Crystal Structure Data* (Journal of the Franklin Institute, February, March, April, 1923, vol. 195, pp. 183-210, 349-365, 531-552). The use of information furnished by the theory of space-groups in studying the arrangement of atoms in crystals has thrown a new light on the structure of crystals. Hitherto it was necessary to be content with the determination of a possible structure which would account for a few limited data taken in a haphazard fashion, but space-group results permit the detailed consideration of all the atomic arrangements possible for a crystal, and offer the opportunity of choosing experimental data in such a manner that they will select the correct structure. Since there is such a great difference between the worth of studies of crystal structures carried out by these two different procedures, and since most of the work that has been done proceeds from the older point of view, a survey of existing crystal data is urgently needed, and the paper aims at providing a discussion of these. Eventually all the old determinations must be more or less thoroughly reworked from the standpoint of space-group theory, and for this reason its introduction is greatly to be desired. The first part of the paper is devoted to the discussion of the crystal structures of the metals of the vertical groups.

P. Pfeiffer, *Space Conceptions in Inorganic Chemistry* (Stahl und Eisen, March 8, 1923, vol. 43, pp. 334-340). The author reviews the present knowledge of the structure of inorganic bodies, and in particular of the structure of crystals of which metals are built up, in the light of the researches of von Laue, Bragg, Debye, Scherrer, and Rinne.

E. C. Bain, *The Nature of Solid Solutions* (Chemical and Metallurgical Engineering, January 3, 1923, vol. 28, pp. 21-24). The atomic arrangements of the metals and metalloids have been investigated. Solid solutions usually exhibit space lattices of their dominant member, slightly distorted. In some systems the transition zones show two co-existing lattices where atoms of each constituent replace the others in its own space lattice.

H. C. H. Carpenter, *The Production of Single Metallic Crystals and Some of their Properties*. (This Journal, p. 175.)

F. Koref, *The Further Growth of Metallic Crystals by Precipitation from the Gaseous State* (Zeitschrift für Elektrochemie, December 1, 1922, vol. 28, pp. 511-517). A mixture of sesquichloride of tungsten (volatilising at 347° C.) and hydrogen was passed over a red-hot tungsten wire consisting of a single crystal. Under suitable experimental conditions the metallic tungsten deposited from the gas caused the single crystal to grow, and it was found that by this means an enlargement of a metallic crystal could be produced.

E. A. Owen and G. D. Preston, *Modification of the Powder Method of Determining the Structure of Metal Crystals* (Paper read before the Physical Society of London, December 8, 1922). Plates of aluminium, iron, copper, lead, and magnesium were examined by means of the Bragg X-ray spectrometer. The maxima observed in the spectra were sufficiently intense to measure with accuracy, and the crystalline structure of the materials examined was readily determined. A few of the results obtained by the method are included in the paper.

V. Kohlschütter and K. Steck, *Crystal Formation in Colloid Metals* (Zeitschrift für Elektrochemie, December 1922, vol. 28, pp. 554-568).

E. C. Bain, *Cored Crystals and Metallic Compounds* (Chemical and Metallurgical Engineering, January 10, 1923, vol. 28, pp. 65-69).

Stainless Steels ; Acid-Resisting Alloys.—V. S. Polansky, *Bibliography of Stainless Steel and Iron* (Forging and Heat-Treating, December 1922, vol. 8, pp. 560-565). A list of references to the literature on stainless steel in the Carnegie Library at Pittsburg is published. Practically all articles, papers, books, and patent specifications published since 1919 are referred to.

J. H. G. Monypenny, *Stainless Steel* (Proceedings of the Cleveland Institution of Engineers, Session 1922-23, No. 5, pp. 155-187 : Iron and Coal Trades Review, March 9, 1923, vol. 106, pp. 342-343). The properties and some of the engineering applications of stainless steel are discussed under the following headings : Corrosion differences,

effects of heat-treatment, air-hardening properties, resistance to corrosion, mechanical properties and composition, and applications.

J. H. G. Monypenny, *The Resistance to Corrosion of Stainless Steel and Iron* (Paper read before the Faraday Society, Joint Meeting at Sheffield, April 13, 1923). The constitution, properties, composition, and treatment of stainless steels and iron are fully dealt with, and the results of tests to show the resistance of stainless iron and steel to various corroding agents are given.

W. H. Hatfield, *Stainless Steel, with Some Consideration of its Application to the Glass Industry* (Paper read before Society of Glass Technology, January 17, 1923). The properties and composition of stainless steels are described, with some account of the recent developments in their production. They can be made use of in the glass industry on account of their resistance to scaling and strength at high temperatures.

H. Brearley, *Stainless Steel* (Lecture before the Chelmsford Engineering Society, January 18, 1923, p. 23). The composition, structure, mechanical properties, and applications of stainless steel are outlined.

G. Tammann and E. Sotter, *The Electrochemical Behaviour of Iron-Chromium, Iron-Molybdenum, and Iron-Aluminium Alloys* (Zeitschrift für anorganische Chemie, 1923, vol. 127, pp. 257-272).

J. F. Kayser, *Alloys Resistant to Corrosion* (Paper read before the Faraday Society, April 13, 1923). A short account is given of the heat- and acid-resisting properties of nickel-chromium and nickel-iron-chromium alloys.

J. A. Aupperle, *Corrosion-Resisting Iron and Steels* (Chemical and Metallurgical Engineering, April 16, 1923, vol. 28, pp. 681-682). The author deals briefly with the corrosion-resisting properties of commercially pure iron, stainless steel, and silicon irons.

H. E. Diller, *Acid-Resisting Metal Unique* (Foundry, January 15, 1923, vol. 51, pp. 47-52). An account is given of the practice of the Duriron Co., Dayton, Ohio, for the production of high silicon iron castings. The metal is of the following composition: silicon, 14.25 to 14.75; sulphur, about 0.03; phosphorus, about 0.10; manganese, about 0.25; and total carbon less than 1.0 per cent. Melting is carried out in an air furnace. The basis of the original charge is ferro-silicon containing 13 to 14 per cent. silicon, 0.02 to 0.03 sulphur, 0.08 to 0.1 phosphorus, and 0.34 manganese. This is melted with the required amount of 20 to 50 per cent. ferro-silicon to bring the bath up to the desired percentage of silicon. It is necessary to pig the first melt owing to excess carbon, which is prevented from burning out by the large percentage of silicon. The metal is remelted and poured into castings. The production of pipes from this metal is described. The castings cannot be machined, but they can be successfully welded.

P. D. Schenck, *Acid-Resisting Iron* (Chemical and Metallurgical Engineering, April 16, 1923, vol. 28, p. 678). The composition, properties, and uses of high silicon irons are briefly dealt with.

W. Mason, *Silicon-Iron Acid-Resisting Castings* (Metal Industry, October 6, 1922, vol. 21, pp. 323-326). The nature and uses of silicon-iron acid-resisting alloys, especially their use in the chemical industry, are discussed.

H. C. Knerr, *Duralumin* (Transactions of the American Society for Steel Treating, October 1922, vol. 3, pp. 13-42). The author outlines the manufacture, composition, chemical and physical constitution, mechanical and thermal treatment, and industrial applications of duralumin. A bibliography is appended of recent information dealing with this alloy.

W. B. Stout, *Duralumin: Its Properties and Commercial Possibilities* (Transactions of the American Society for Steel Treating, November 1922, vol. 3, pp. 226-230). The composition, properties of duralumin, and its application to aircraft construction, are briefly discussed.

Duraloy (Iron Age, December 14, 1922, vol. 110, p. 1567). Brief particulars are given of this product, a chromium-iron alloy. It possesses resistance to corrosion under certain conditions, high tensile strength at high temperatures, and hardness and toughness offering marked resistance to wear and abrasion. The metal will resist oxidation up to 2100° F., and can be produced in practically every form, including castings, rolled or forged bars, sheet wire and tubing. The composition is not stated.

Corrosion—Prevention of Corrosion.—W. H. Hatfield, *Corrosion as Affecting the Metals used in the Mechanical Arts* (Paper read before the Sheffield Association of Metallurgists and Metallurgical Chemists, December 5, 1922: Engineer, December 15, 1922, vol. 134, pp. 639-643). The author describes the results of an investigation to test the effect of a number of corroding media on a series of pure irons, carbon steels, alloy steels, cast iron, 30 per cent. nickel steel, 14 per cent. chromium steel, nichrome, and a selection of non-ferrous alloys. Micrographs of all the specimens are given, and the various metals tested are found to divide themselves into two types: homogeneous, consisting of one metal or solid solution; and heterogeneous, consisting of two or more constituents. Apart from the 30 per cent. nickel steel and Monel metal, which may be looked upon as consisting of one phase, the homogeneous materials are readily attacked by many reagents, and it is among the heterogeneous alloys that the most likely fields for further investigation will be found. Standard corrosion tests were made by subjecting the specimens for twenty-four hours to the action of hydrochloric acid, nitric acid, and sulphuric acid. Further tests were made with the following agents: running water, wetting and drying, steam at 100° C. in presence of oxygen, 5 per cent. citric acid, 5 per cent. ammonium chloride, 1 per cent. magnesium chloride, sea-water, vinegar, 33 per cent. acetic acid, 10 per cent. sodium sulphate solution, 5 per cent. magnesium

sulphate solution, and 33 per cent. sodium hydroxide. The whole of the results are summarised in tables. The experiments show that there are now available steels and alloys effective in resisting ordinary corroding influences. The different materials, while in some cases each resisting the same agents, do not give an equal response to other agents. It is essential that actual practical experiments be made in connection with the particular intended application of the steel or alloy, since not only composition, but also concentration temperature and extraneous influences must be considered. No obvious law, or set of laws, or sufficiently satisfactory theory is at present available to render effective aid to an investigator. A considerable amount of work was also done to determine the relation which might exist between the electrode potential and solubility, and the main conclusions reached are that when rapid solution takes place the potential is highly negative; when the potential is highly positive very little corrosion or chemical action takes place; otherwise the magnitude of the potential gives no indication of the solution properties of the metal.

W. H. Hatfield, *Corrosion of Industrial Metals* (Paper read before the Faraday Society, April 13, 1923). The author gives the results of a variety of corrosion tests made on twenty-one different metals and alloys in common use. The tests show conclusively that there are now available steels and non-ferrous alloys effective in resisting ordinary corroding influences, but no general rules can be laid down on the corrodibility or acid-resisting powers of any metal or alloy. Many alloys which are homogeneous in structure are readily attacked by many reagents, while some which are decidedly heterogeneous are among the most resistant: for example, high silicon iron, nichrome, and stainless steel.

F. N. Speller and V. V. Kendall, *New Method of Measuring Corrosion in Water* (Journal of Industrial and Engineering Chemistry, 1923, vol. 15, pp. 134-139). In confirmation of previous investigations, the corrosion of steel in natural waters is found to be directly proportional to dissolved oxygen concentration, and the authors have devised a new method of measuring corrosion based on this law. The method consists in cooling the water under pressure and determining the amount of dissolved oxygen by the Winkler method at the beginning and end of a pipe line, the drop in dissolved oxygen concentration being a measure of the corrosion. The effect of the velocity of flow upon corrosion was determined for velocities ranging from 0.0043 to 8 feet per second, by experiments in steel pipes. An appreciable increase of corrosion took place with an increase in velocity, curves showing the comparative rate of corrosion in steel pipes at temperatures from 15.5° to 77° C. There appears to be a critical velocity range in which corrosion increases rapidly, followed by a more gradual increase until a maximum is reached. With increasing size of pipe the rate of corrosion decreases, other factors remaining the same.

R. E. Wilson, *Mechanism of the Corrosion of Iron and Steel in*

Natural Waters and the Calculation of the Specific Rates of Corrosion (Industrial and Engineering Chemistry, February 1923, vol. 15, pp. 127-133). Three fundamental reactions are involved in the corrosion of iron and steel, and though a number of variables have been found by experiment to have an effect on the rate of corrosion, the entire field may be divided into three ranges, according to which of the three fundamental reactions is the controlling one. In each range the variables determining corrosion are few in number and differ generally from those which control corrosion in the other ranges. In alkaline solutions corrosion is always comparatively slow, and hydrogen ion concentration and temperature are the two most important variables. In natural waters the reaction $2\text{H} + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$ determines the rate of corrosion and makes oxygen concentration and velocity of flow the most important variables; temperature is a factor of secondary importance, and hydrogen ion concentration and the nature of the metal are negligible. In acid solutions the reaction $2\text{H} \rightarrow \text{H}_2$ becomes the controlling one, and the most important variables become hydrogen overvoltage, the nature of the impurities in the metal, temperature, and hydrogen ion concentration. For corrosion in natural waters it is proposed to define the specific rate of corrosion as the loss in weight in milligrammes per square centimetre per year, per cubic centimetre of oxygen per litre. It is pointed out that it is unsafe to draw practical conclusions from accelerated corrosion tests.

O. Bauer, *Corrosion Tests on Two Steel Rails* (Mitteilungen a.d. Materialprüfungsamt, 1922, vol. 40, pp. 65-71). Two kinds of rails as used on German railways were tested after being in service for a number of years. Rail I. contained 0.43 carbon and 0.12 silicon, and after twenty-five years' service had rusted away in the web and foot, but the running surface was very little worn. Rail II. contained 0.21 carbon and 0.50 silicon, and after fifty years' service was badly worn on the running surface, but only slightly corroded in the web and foot. Experiments showed that the steel of rail I. was more easily attacked by 1 per cent. sulphuric acid than that of rail II., but it could not be established whether this was due to its higher carbon and lower silicon or to either of these constituents alone.

U. R. Evans, *The Mechanism of the So-called Dry Corrosion of Metals* (Paper read before the Faraday Society, Joint Meeting at Sheffield, April 13, 1923). Experiments on the behaviour of apparently dry metals, roughened with emery, show that no corrosion occurs when they are kept over sulphuric acid, and only slow superficial corrosion occurs when they are kept over water. The rate of attack is greatly increased by the presence in the air of volatile electrolytes, sulphur dioxide being most dangerous to iron and nickel, and ammonia to copper and its alloys. Hydrogen sulphide and carbon dioxide somewhat increase the rate of corrosion of iron, but produce only superficial changes on other metals. Contrary to a common belief, the presence of ammonia does not cause corrosion of iron.

J. Newton Friend, *Recent Progress in the Study of Corrosion* (Journal of the Birmingham Metallurgical Society, vol. 8, No. 6, pp. 243-250).

T. S. Fuller, *The Corrosion of Iron and Steel* (Transactions of the American Society for Steel Treating, October 1922, vol. 3, pp. 94-97). The author briefly reviews some of the theories advanced to explain the phenomena of corrosion.

A. Pickworth, *Corrosion—with Special Reference to the Ferrous Metals and Deterioration of Ships* (Transactions of North-East Coast Institution of Engineers and Shipbuilders, 1921-22, vol. 38, pp. 509-528).

W. Ramsay, *Modern Conceptions of Corrosion* (Transactions of the Liverpool Engineering Society, 1921, vol. 43, pp. 63-77). The various theories as to the causes of corrosion are reviewed.

W. D. Bancroft, *Preliminary Notes on Corrosion* (Proceedings of American Society for Testing Materials, 1922, vol. 22, Part 2, pp. 232-236). Suggestions are made as to the development of rapid methods for studying corrosion.

W. Bertelsmann, *Corrosion of Gas Pipes and Apparatus* (Gas und Wasserfach, 1922, vol. 65, pp. 686-690). Gas pipes laid in the ground, in brickwork, or on damp walls will corrode on the outer surfaces. In moist soil, containing salts or free carbon dioxide, iron pipes will become spongy, but the presence of air diminishes the effect. The pipes should be laid in porous soil and embedded in sand. Corrosion from the inside outwards is caused by the action of oxygen and carbon dioxide, also hydrocyanic acid, sulphur compounds, and ammonia in the presence of moisture. Town gas contains sufficient moisture to set up this corrosion.

J. Newton Friend, *The Preservation of Iron and Steel by Means of Paint* (Journal of the Oil and Colour Chemists Association, October 1922, vol. 5, pp. 263-307). The author deals mainly with experiments he had carried out at Worcester and Birmingham. The functions of the two constituents of paint, namely, a liquid vehicle and a pigment, are discussed. The author's experiments had shown that several thin coats of paint retarded corrosion better than one thick coat. Actually the best results were obtained with one thin and one thick coat of paint, so far as prevention of corrosion of steel was concerned.

E. Liebreich, *Electroplating with Chromium* (Zeitschrift für Metallkunde, September 1922, vol. 14, pp. 367-368). The difficulties in plating steel and other metals with chromium were solved by studying the causes of the regular fluctuations in the tension of the bath which always take place when using chromic acid as the electrolyte, notwithstanding that a constant resistance of the external circuit is maintained. It was found that the reason for these fluctuations lay in the fact that with chromic acid and other salts of chromium the deposition of chromium at the cathode proceeded by jumps. The curve of current tension appears to divide into several parallel branches, of which only the outside curve corresponds to the separation of metallic

chromium; as the concentration of the electrolyte changes, the potential jumps across from one curve to its neighbour. This suggested the use of suitably reduced chromium salt solutions, and it was then found that the deposition of chromium at the cathode proceeded steadily. Diagrams of the current tension curves are given, showing their separation into several parallel curves, using the ordinary solutions of chromium, and that they converge into a single curve when the reduced solution is used. The degree of concentration is not stated.

F. C. Kelly, *Chromising* (Paper read before the American Electrochemical Society, May 1923). A brief summary is given of previous work on the diffusion of metals, and the process of chromising and its effect on the physical and chemical properties of iron are described in detail. The practical application of this process is also considered. The process consists in packing the material to be treated in a powdered mixture of 45 per cent. of alumina and 55 per cent. of chromium by weight, and then heating at 1300° to 1400° C. in hydrogen, in vacuum, or in some neutral atmosphere for varying periods, depending upon the penetration of chromium desired. Iron and steel of high carbon content do not chromise well, as the carbon retards the penetration of the chromium. Chromised iron shows great resistance to acid attack and corrosion, takes a high polish, and is soft even where large percentages of chromium are present. The structure of chromised iron is described.

W. P. Wood, *Corrosion of Rust-Proofed Iron and Steel* (Chemical and Metallurgical Engineering, April 30, 1923, vol. 28, pp. 769-772). The results are given of an investigation upon the corrosion rates of iron and steel immersed in water when unprotected and when protected by calorising, parkerising, sherardising, galvanising, and by the electrolytic zinc process. The presence of oxygen apparently causes an exaggerated initial corrosion in iron and low-carbon steel. The presence of a small amount of chlorine in tap-water causes a slight but not serious increase in corrosion rates of immersed metals. The composition of iron and steel does not affect noticeably the corrosion rate when metal is immersed in water. This applies particularly to the presence of copper. Different surface conditions of a metal tend to become equalised over a period of time and the corrosion rate to become steady and uniform when the metal is in the presence of large amounts of oxygen. The presence of large amounts of oxygen does not appear to increase the tendency toward pitting in a corroding piece of iron or steel. Galvanising is the best method of protection against rusting when immersed in water saturated with oxygen.

L. C. Morrow, *Parkerising—A Rust-Proofing Process* (American Machinist, European Edition, October 28, 1922, vol. 57, pp. 361-364). The method of coating iron and steel by the Parker process is described and illustrated. Parts to be treated are first pickled and cleaned and then immersed in a solution consisting of phosphoric acid in quantities of less than $\frac{1}{2}$ of 1 per cent., phosphates of iron and manganese, and

water about 99 per cent. Manganese dioxide is added to serve as an oxidising agent, its function being to accelerate the reaction by removing the hydrogen in the form of water. The bath is maintained at a temperature of 210° F. The surface of the treated parts consists entirely of iron phosphates.

B. Zschokke, *A New Process for the Protection of Iron and Metal Structures against Rust* (Revue de Métallurgie, Mémoires, March 1923, vol. 20, pp. 165-174). Various methods are described for the protection of iron against corrosion, in which the chief agents are chromium salt solutions. Their use for ferro-concrete bars is recommended.

J. H. Young, *Asbestos-Protected Metal* (Paper read before the American Institute of Chemical Engineers: Iron Age, April 19, 1923, vol. 111, p. 1106). The characteristics and uses of asbestos-covered steel sheets are dealt with. The sheet is first passed through a vat of asphalt maintained at a temperature of 350° F. As the coated steel emerges from this vat, asbestos felt, previously saturated with asphalt, is pressed on to both sides of the sheet and folded around the edges, thus completely sealing it. The next operation consists in running the felted sheets through coating rolls, which operate at a temperature of about 425° F., and applying the top waterproofing coat. The top coating is compounded bitumen of the so-called stearin pitch type. The asbestos-protected sheets are strong, durable, and light in weight, and have a fairly low thermal conductivity.

Enamelling.—W. F. Wenning, *Zirconia in Sheet-Iron Enamels* (Journal of the American Ceramic Society, May 1923, vol. 6, pp. 102-104). Zirconia, having properties similar to alumina and silica, can be used in place of these ingredients in ordinary ground coat enamels. A replacement up to 10 per cent. of zirconia changes the working property of the enamels very little, and the enamels are stronger and more elastic with better adhesion to the steel. White zirconia is of value on account of its opacifying property, and zirconia used in low fluoride enamels produces exceptionally good opacity and whiteness. Such enamels are more acid-resistant and are not affected by a reducing furnace heat.

Enamelling Sheets and Castings (Iron Trade Review, January 18, 1923, vol. 72, pp. 223-226). The enamelling plant and methods employed by the Wrought Iron Range Company, St. Louis, are described and illustrated. Improved methods of spraying are employed, and muffle furnaces are used for burning on the enamel.

How to Enamel Stove Parts (Foundry, February 1, 1923, vol. 51, pp. 93-96). An illustrated description of the equipment and methods employed in enamelling stove parts in an up-to-date American foundry.

M. E. Manson, *Effect of Sources of Pig Iron upon the Enamelling of Cast Iron* (Journal of the American Ceramic Society, November 1922, vol. 5, pp. 806-810). The chemical composition of cast iron articles intended to be enamelled is of considerable importance. Experiments

show that castings with a low content of combined carbon blister badly, but the enamelling was quite satisfactory where the combined carbon amounted to 0.30 per cent. It was found that any castings with less than 0.15 per cent. of combined carbon will develop blisters, but it has not been definitely determined whether the blistering is directly due to this, or to the presence of some other constituent not generally determined in cast iron.

Galvanising.—D. M. Strickland, *A Method for Determining the Spelter Coating on Iron and Steel Sheets by Measuring the Rise in Temperature of the Acid Employed* (Proceedings of American Society for Testing Materials, 1922, vol. 22, Part 2, pp. 227–231). A new method for determining the amount of spelter coating is described, the value of the method lying in the fact that coating weights can be determined without use of the analytical balance. A galvanised specimen is immersed in a measured amount of acid, the maximum rise in temperature being recorded. Each one-tenth degree rise in temperature is equivalent to a definite weight of zinc.

Improved Wire-Galvanising Equipment (Iron Age, December 14, 1922, vol. 110, pp. 1563–1564). Illustrated particulars are given of the wire-galvanising plant recently installed in a Canadian works. The annealing and spelter pans are each 28 feet in length, it being claimed that large pans result in a better and more even operation and are more economical.

W. R. Bean, *Deterioration of Malleable in the Hot-Dip Galvanising Process* (Paper read before the American Institute of Mining and Metallurgical Engineers, February 1923). It is shown that the embrittling effect produced in malleable iron by hot galvanising is intimately connected with the phosphorus and silicon contents of the iron. In general, iron with under 0.15 per cent. phosphorus and under 0.80 per cent. silicon will withstand the process best and show practically no deterioration. With a phosphorus content of about 0.10 the silicon may be as high as 1.20 per cent. without serious effect from galvanising. High phosphorus high silicon irons are practically certain to be embrittled by galvanising. The brittleness is due to a thermal effect resulting from the quenching after the galvanising operation. The exact mechanism of the deterioration, whether it is a species of internal strain or a segregation of the phosphorus and silicon at the grain boundaries, is not known. The brittleness may be avoided by the control of the phosphorus and silicon, by the use of high temperature quenching baths (300° to 600° F.) after galvanising, or by eliminating quenching entirely. Micros are given showing the brittleness of galvanised material to be due to intergranular weakness.

Pickling Tin-Plates.—H. J. Bailey, *Chemistry in Relation to Tin-Plate Manufacture* (Paper read before the Swansea Technical College: Iron and Coal Trades Review, April 20, 1923, vol. 106, p. 560). The reactions incidental to the pickling of tinplates are discussed.

Electrodeposition.—M. R. Thompson, *The Effect of Iron on the Electrodeposition of Nickel* (Paper read before the American Electrochemical Society, May 1923). A number of previous investigations are reviewed, and it is concluded that the results may have been influenced by lack of regulation of the hydrogen ion concentration of pH. It is shown that, if the pH is properly controlled, the presence of iron in nickel solutions does not necessarily cause cracking or peeling of the deposits. Deposited iron has a primary effect upon the crystalline structure of nickel deposits, rendering the latter fine-grained and therefore probably harder, although more brittle.

H. D. Hineline, *Notes on the Electrodeposition of Iron* (Paper read before the American Electrochemical Society, May 1923). Experiments were carried out to determine the type of plating bath that would give good deposits of iron of substantial thickness on rubber articles. A saturated bath of ferrous and calcium chlorides, containing chromous chloride and hydroquinone as reducing agents, gave the best results.

E. J. L. Holman, *Note on a Value for the Surface Tension of Iron Sulphide*. (This Journal, p. 517.)

Laboratory Apparatus.—C. R. Darling, *Electrical Resistance-Furnaces and their Uses* (Journal of the Royal Society of Arts, March 23, 1923, vol. 71, pp. 324–336). The chief factor in the development of the metal-wound resistance-furnace was the introduction of nickel chromium alloys. These alloys may be heated for long periods up to 1000° C. without oxidising or undergoing other deteriorations. They offer a nearly constant resistance to electricity at all temperatures. Several types of these furnaces are described. The need for a furnace giving temperatures up to 2000° C. has led to the design of carbon resistance-furnaces. Typical furnaces of this type are considered.

W. M. Mitchell, *The Metallurgical Microscope* (Forging and Heat-Treating, January, February, 1923, vol. 8, pp. 63–66, 106–112). The use and limitation of lenses, various methods of illumination of the objective, photomicrography, and accessories of microscopic work are dealt with.

H. B. Wrighton, *Objectives for Metallurgy* (Paper read before the Royal Microscopical Society, March 28, 1923). The design of objectives to meet the requirements of metallurgical microscopy is discussed.

D. Flir, *A New Radiation Pyrometer* (Iron Age, May 3, 1923, vol. 111, pp. 1302–1303). An illustrated description is given of a new pyrometer known as the ardometer. It consists of a telescope, with objective and ocular lens, between which is located a small thermoelement in a sealed glass bulb. The hot junction of this thermoelement is soldered to a thin blackened disc; the free ends of the couple being connected to a galvanometer, either indicating or recording. The instrument weighs only one pound.

P. Chevenard, *New Applications of the Dilatometric Pyrometer to the Thermal Analysis of Steels* (Memoir presented to the Liège Congress,

June 1922: *Revue de Métallurgie, Mémoires*, Sept. 1922, vol. 19, pp. 546-561). A new form of differential pyrometer is described for the thermal analysis of alloys by the Roberts-Austen method. A sample of the metal to be investigated, and a sample of identical dimensions made from an inert metal, are placed side by side in a laboratory furnace, and after being heated together, are uniformly cooled together. The inert metal may be a ferro-nickel alloy with 25 per cent. of nickel, there being considerable advantage in using a metal the calorific capacity of which differs but little from that of the alloy. Photographs and diagrams of the apparatus employed are given, together with diagrams of the dilatometric curves obtained.

U. Retzow, *Optical Pyrometers and their Application* (*Zeitschrift des Vereines Deutscher Ingenieure*, February 24, 1923, vol. 67, pp. 179-181).

H. J. French, *A Recording Chronograph for the Inverse-rate Method of Thermal Analysis* (Transactions of the American Society for Steel Treating, March 1923, vol. 3, pp. 640-648). A description is given of a direct plotting chronograph for the inverse-rate method of thermal analysis. It is in use at the United States Bureau of Standards for determining transformations in various carbon and alloy steels under varying thermal treatments. Typical curves obtained by the use of the apparatus are reproduced.

G. Keinath, *The Subjective Defects in Optical Pyrometers* (*Stahl und Eisen*, January 4, 1923, vol. 43, pp. 9-12). A disadvantage attaching to the use of optical pyrometers is that different observers obtain different readings with the same instrument. The reasons for this are considered to be mainly due to want of practice, and the author draws attention to the various points to be observed in order to eliminate errors in taking readings.

An illustrated description has appeared of the works laboratories of the Schneider Company at Harfleur (*Revue de Métallurgie, Mémoires*, February 1923, vol. 20, pp. 73-87). These are equipped for all the ordinary operations, and for metallography, photography, and for testing. An interesting note is given in regard to the radiographic examinations carried out, which includes a number of illustrations showing the defects which can be detected by X-ray examination.

Metallurgical Education.—*Symposium on Metallurgical Education* (Transactions of the American Society for Steel Treating, February 1923, vol. 3, pp. 534-568). A number of papers were presented at the meeting held at Detroit in October 1922, including the following: *Notes on Metallurgical Education*, by J. A. Mathews; *Education of Machinists and Tool-Makers in Heat-Treating*, by H. B. Knowlton; *A Course in Metallurgy for Metallurgical Engineers*, by H. M. Boylston.

CHEMICAL ANALYSIS.

Analysis of Iron and Steel.—L. Losana and C. Cimino, *Sampling of Cast Iron* (Giornale di Chimica Industriale ed Applicata, 1922, vol. 4, pp. 521–525). Various methods of sampling cast iron were tried in order to discover which gave the most accurate results. The best method to ensure accuracy is to crush the whole sample obtained by drilling to as fine a powder as possible, and to mix well before taking portions for analysis.

C. E. Williams and A. E. Anderson, *The Determination of Metallic Iron in Sponge Iron* (Journal of Industrial and Engineering Chemistry, November 1922, vol. 14, pp. 1057–1060). The methods commonly employed for determining the copper-precipitating value are satisfactory if they are performed under conditions that hold in plant operation, but in most cases they are not satisfactory for determining the metallic iron content. When a copper sulphate solution is treated with metallic iron, more than an equivalent weight of copper is precipitated if the solution is either neutral or contains less than 0.075 per cent. sulphuric acid, whereas less than an equivalent weight of copper is precipitated if the solution contains more than 0.075 per cent. sulphuric acid. In the method described by the author, precipitation of the copper from a neutral solution is preferred, but if the solution has acidity this is not important so long as the acidity is not sufficient to cause solution of any oxide of iron which might be present. The method recommended is both rapid and accurate.

Estimation of Minute Percentages of Iron in Foundry Materials (Foundry Trade Journal, November 9, 1922, vol. 26, p. 383). The usual method for the determination of minute percentages of iron in materials such as silica bricks, sand, and limestone is described, and details are given of the following modified method: After dissolving the material by one of the usual methods, the solution is diluted considerably, and made to contain about 5 per cent. of nitric acid. The solution is treated with potassium sulphocyanide, and when the dirty reddish colour develops, about 10 c.c. of ether are added and the liquor thoroughly shaken up. By shaking up with ether the sulphocyanide compound of potassium, iron, &c., is decomposed and the iron sulphocyanide dissolved out alone. The standard iron solution preferred for this work contains about 0.01 gramme of iron per litre, and is made up by dissolving ammonium ferro-sulphate in distilled water containing a little sulphuric acid.

G. E. F. Lundell and J. I. Hoffman, *Determination of Phosphorus in*

Iron and Steel (Industrial and Engineering Chemistry, January, February, 1923, vol. 15, pp. 44-47, 171-173). The application of a reduction method and an alkalimetric method to the determination of phosphorus in iron and steel is discussed. The reduction method is slightly more reliable than the alkalimetric method with solutions containing no interfering elements, but the advantage does not outweigh its inconvenience. The alkalimetric method yields under severe conditions values sufficiently accurate for technical purposes.

P. V. Kline, *Analyses of Iron and Steel* (Iron Trade Review, October 26, 1922, vol. 71, p. 1124). The determination of phosphorus by the alkalimetric method, and the determination of manganese by the persulphate method, are described.

V. E. Hillman, *Determine Sulphur by Evolution Method* (Foundry, October 15, 1922, vol. 50, pp. 837-838). The evolution method for determining sulphur in iron and steel is described.

F. Nikolai, *Accurate and Rapid Method for the Determination of Sulphur in Iron and Steel* (Chemiker Zeitung, 1922, vol. 46, pp. 1025-1026). The sample is treated with hydrobromic acid (47.4 HBr) in a small flask connected by a glass joint with a tube, the first part of which acts as an air condenser and then leads down into a receiver containing 2.5 per cent. sodium hydroxide solution. The temperature of the mixture of iron and hydrobromic acid is raised to boiling point, and the hydrogen sulphide liberated is absorbed in the sodium hydroxide solution which is titrated with iodine solution after adding 10 c.c. of potassium iodide solution and some starch. The operation requires twenty to twenty-five minutes, and the results agree very well with those obtained by Fresenius's method. The results are higher than those given when using either dilute or concentrated hydrochloric acid.

G. Chaudron and L. Blanc, *Estimation of Oxygen in Steel* (Comptes Rendus, 1922, vol. 175, pp. 885-887). In the method of estimating the oxygen in steel by passing a current of dried electrolytic hydrogen over the heated metal and weighing the water thus formed the experimental error may be as great as 10 per cent., owing to the very small quantity of water to be weighed. A portion of the oxygen may also be converted into carbon monoxide. The addition of other metals to the steel to enable the estimation to be made at a lower temperature makes no difference. If oxide of manganese or silicon is present in the steel the reduction is incomplete.

L. Jordan and F. E. Swindells, *The Determination of Combined Nitrogen in Iron and Steel and the Change in Form of Nitrogen by Heat Treatment* (United States Bureau of Standards, 1922, Scientific Paper, 457). The only form of nitrogen ordinarily determined in steel is that combined as nitride, either of iron or of some of the other constituents. The usual method for the determination of the combined nitrogen is some modification of the Allen method. Evidence is given of the increase with heat treatment of the combined nitrogen in certain

steels. It is probable that this increase is the result of the conversion of uncombined nitrogen to nitride nitrogen by heat treatment, and that nitrogen in two forms was present in the samples in which the increase took place.

A. Eder and H. Eder, *The Determination of Manganese, Chromium, and Nickel in Steel* (Chemiker Zeitung, 1922, vol. 46, pp. 1085-1086).

K. Chalupny and K. Breisch, *Determination of Nickel in Steels* (Chemiker Zeitung, 1922, vol. 46, p. 1043). Nickel steel containing manganese cannot be treated by the method of Rubricius, as the manganese is precipitated by ammonia, even in the presence of ammonium nitrate. In such cases it is best to precipitate the nickel in the presence of tartaric acid and the glyoxine precipitate dissolved in warm dilute hydrochloric acid, boiled with a little 3 per cent. hydrogen peroxide solution, and the nickel is precipitated electrolytically after adding excess of ammonia and ammonium sulphate.

E. P. Barrett and J. D. Sullivan, *A Simple Method for the Determination of Tin in Iron and Steel* (United States Bureau of Mines, 1923, Reports of Investigations, 2459).

K. Seel, *The Analysis of Alloys Containing High Percentages of Tungsten* (Zeitschrift für angewandte Chemie, 1922, vol. 35, pp. 643-644).

H. H. Willard and D. Hall, *The Separation and Determination of Cobalt* (Journal of the American Chemical Society, October 1922, vol. 44, pp. 2219-2231, 2237-2253). The separation of cobalt by means of phenyl-thiohydantoic acid, and the gravimetric and volumetric methods of determining cobalt, are described. Cobalt may be quantitatively separated in one operation from other metals by precipitation with phenyl-thiohydantoic acid in slightly ammoniacal solution. In the presence of iron the precipitate is rarely entirely free from this impurity, and usually contains from 1 to 5 milligrammes, regardless of the amount originally present. This does not, however, interfere with the volumetric determination of cobalt. Nickel is always partially precipitated. The cobalt precipitate does not always have a definite composition. It is probably contaminated with cobalt sulphide, thus making it necessary to convert the cobalt into some more definite form. For the determination of cobalt, volumetric methods are in general the most accurate and satisfactory. The most accurate method involves the oxidation of cobalt to cobaltic hydroxide in strongly alkaline solution by means of perborate or hydrogen peroxide, followed by its volumetric reduction to a cobaltous salt. Cobalt in alloy steels was determined volumetrically after separation by phenyl-thiohydantoic acid.

J. A. Halladay and T. R. Cunningham, *Experiments Relative to the Determination of Uranium by Means of Cupferron* (Paper read before the American Electrochemical Society, May 1923). A description is given of experimental work concerning the determination of uranium by precipitation with cupferron. It is shown that quadrivalent uranium can be quantitatively precipitated by cupferron from solutions

containing from 4 to 8 per cent. H_2SO_4 (specific gravity 1.84), that aluminium, calcium, magnesium, and phosphorus remain in solution and can be completely separated from the uranium by filtration, and that the precipitate of $\text{U}(\text{C}_6\text{H}_5\text{N}_2\text{O}_2)_4$ can be quantitatively converted to U_3O_8 by ignition.

W. F. Meggers, C. C. Kiess, and F. J. Stimson, *Practical Spectrographic Analysis* (United States Bureau of Standards, 1922, Scientific Paper 444). A brief review of various methods which have been proposed for chemical analyses by means of the spectrum. A detailed description is given of the principle, apparatus, and procedure employed.

W. A. Forbes, *Value of Chemistry in the Iron and Steel Industry* (Paper read before American Iron and Steel Institute, May 25, 1923, 22 pp.).

Analysis of Refractories.—S. D. Averitt, *A Rapid Method of Analysis for Dolomite and Magnesite Limestone* (Journal of Industrial and Engineering Chemistry, December 1922, vol. 14, pp. 1139–1140). The method described is an indirect method and does not involve the determination of either calcium or magnesium. The functions concerned are: the neutralising power of the stone as calcium carbonate; the insoluble residue and ammonium precipitate; and the moisture. The method is fully as accurate and somewhat shorter than the usual differential method, which in addition to the neutralising power as calcium carbonate requires the actual determination of the calcium.

The Analysis of Dolomite Bricks (Foundry Trade Journal, February 1, 1923, vol. 27, p. 104). Ammonium chloride in sufficient quantity is required to prevent the carrying down of magnesia with the alumina, and in ordinary dolomites the hydrochloric acid used in taking up the dry mass, and in the double precipitation, is sufficient to form enough ammonium chloride for the above purpose, with only 2 to 3 per cent. of the oxides present. In the case of higher oxide content this is not sufficient, and a method is described to meet these circumstances.

Analysis of Gas.—F. S. Sinnatt and L. Slater, *Source of Error in the Determination of Small Amounts of Carbon Monoxide* (Fuel, 1922, vol. 1, pp. 241–243).

NOTICES OF RECENT BOOKS PRESENTED TO THE LIBRARY.

L. AITCHISON and W. R. BARCLAY. "*Engineering Non-Ferrous Metals and Alloys.*" With an Introduction by Sir George G. Goodwin, K.C.B. 8vo, pp. 300. London, 1923: Henry Frowde and Hodder & Stoughton. (Price 21s.)

The book provides both those who make and those who use non-ferrous metals with some fundamental information regarding these materials. It falls naturally into two parts. The first part deals with non-ferrous metals generally, and the second with the individual metals and alloys in some detail, and more particularly from the point of view of their use in the engineering industries. The properties of the different materials given in detail should indicate to the user a basis upon which to work when making selections of those metals that will fulfil his various purposes and will satisfactorily perform the duties required of them in service. The same information should also be useful in providing a basis upon which the maker may satisfy the requirements of the user. The authors appear to have endeavoured, and very successfully, to present their subject in language familiar to engineers rather than in the terms which have become usage among academic metallurgists. It is likely that for this reason the book will appeal to many practical men who may like to avoid constant reference for the elucidation of unfamiliar terms.

ALVARO ALONZO BARBA. "*El Arte de los Metales.*" (Metallurgy.) 8vo, pp. 288. Translated from the Spanish by Ross E. Douglas and E. P. Matthewson. (First published in Spain in 1640.) New York, 1923: John Wiley & Sons, Inc. London, 1923: Chapman & Hall, Ltd. (Price \$3.50.)

The translators state in their preface to the work that "*El Arte de los Metales*" was written in Spanish by Alvaro Alonzo Barba, Master of Arts, and Curate of the Parish of San Bernardo, Potosi, Bolivia, and is undoubtedly the earliest published work on American metallurgy. Book I. summarises the geological knowledge of Barba's time, but Books II. to V., inclusive, are based on the knowledge acquired by him in many years of active work in mining and ore treatment, in a region which even before his time had yielded many millions of dollars in silver bullion. The excellent work done by the old Spanish metallurgists is well known to engineers of this generation who have had occasion to sample and assay old Bolivian waste dumps. Barba's work was first published in Spain in 1640 and reprinted in 1675 and 1729. English, French, and German translations were made during the seventeenth and eighteenth centuries. The original edition of 1640 is said to have been banned and burnt by the Inquisition, and only three copies of the Madrid quarto are known to exist at the present time, all of which are owned by the British Museum. Those responsible for the present new translation have rendered a valuable service in making this highly interesting work accessible to readers of the English language.

- T. H. BURNHAM. "*Special Steels: Chiefly founded on the Researches regarding Alloy Steels of Sir Robert Hadfield, Bt., and with a Foreword by Him.*" 8vo, pp. 194. London, 1923: Sir Isaac Pitman & Sons, Ltd. (Price 5s.)

The volume constitutes a primer for the use of students, operators, and users of special steels. It reviews current knowledge and practice, and attention has been given to recent developments in the production of special steels. The book is largely founded on the research work discoveries and inventions of Sir Robert Hadfield, including those relating to manganese steel, low hysteresis steel, and other important special products, and it will be of considerable service to those who may wish to study the important subject of special steels.

- U. R. EVANS. "*Metals and Metallic Compounds.*" 8vo. In four volumes. Vol. I.: "Introduction, Metallography, Electrochemistry." Pp. 468. Vol. II.: "Metals of the 'A' Group." Pp. 396. Vol. III.: "The Transition Elements." Pp. 270. Vol. IV.: "Metals of the 'B' Group." Pp. 350. London, 1923: Edward Arnold & Co. (Price, Vol. I. 21s., II. 18s., III. 14s., IV. 18s.)

The book is intended to benefit the advanced student of inorganic and metallurgical chemistry and the industrial chemist, while certain portions, such as those dealing with work-hardening, recrystallisation, the effect of impurities on metals, and corrosion, should prove useful to the engineer. Much of the information presented was hitherto only to be found scattered through the volumes of scientific and technical journals and proceedings, and is now for the first time made available in a convenient form for reference. The first volume of the work is of a general character, consisting mainly of two parts, the study of the metallic state (metallography) and the study of the ionic state (electrochemistry). The metallographic portion includes the effects of deformation, annealing, and alloying on the properties of metals; while the electrochemical portion includes such subjects as the structure of precipitates, the colloidal state, electrodeposition, and corrosion. In Volumes II., III., and IV. the individual metals are dealt with one by one, and the space devoted to each metal is divided into three main sections. In the first the metal and its compounds are discussed from the point of view of the academical laboratory, with no reference to technical processes. The second section deals shortly with the terrestrial occurrence of the metal and the probable mode of formation of its ores. In the third section, beginning from the ore, the processes of concentration and smelting are followed through, and finally the practical uses of the element and of compounds containing it are considered.

- J. N. GOLDSMITH, S. JUDD LEWIS, and F. TWYNAM. "*Optical Methods in Control and Research Laboratories.*" 8vo, pp. 56. Pamphlet. London, 1923: Adam Hilger, Ltd.

The optical methods dealt with in the book are those in which spectroscopes, spectrophotometers, refractometers, and polarimeters are employed. No detailed descriptions of these instruments are included, but in each case references are given to sources of information on these points. The work is confined chiefly to the practical applications of these types of instruments, and is intended as an introduction to their uses, as a guide to their selection, and as an index to further sources of information concerning them.

- W. E. GROUME-GRJIMAILO. "*The Flow of Gases in Furnaces.*" 8vo, pp. 399. Translated from Russian into French by L. Dlougatch and A. Rothstein, and translated from the French into English by A. D. Williams. With an Appendix upon the Design of Open-Hearth Furnaces. New York, 1923: John Wiley & Sons, Inc. London, 1923: Chapman & Hall, Ltd. (Price 27s. 6d.)

The title of this work is an abbreviated paraphrase of the title of the French edition, the English rendering of which is, "An Essay upon a Theory concerning Hot Gases in Furnaces based upon the Laws of Hydraulics." The work was originally published in the *Journal of the Russian Metallurgical Society* in 1911, and the French translation appeared in book form in 1914. As its title indicates, the book treats of the development of the flow laws of heated gases and the application of those laws to the rational design of furnaces, and according to the author a large number of furnaces have already been designed on his principles and put into successful operation. His idea of regarding every furnace as a hydraulic reservoir has had a considerable influence upon the design of new forms of furnaces. From a large number of examples given in the book it is clearly shown that only those furnaces in which the circulation of the gases corresponds with the natural laws will work in a satisfactory manner. The Appendices to the work contain among other matter the formula for the inverted weir according to the computation of J. C. Yesmann (Petrograd), the Smithsonian tables of the volume of gases, and A. D. Williams' own monographs on the design of open-hearth furnaces, and on the design of hot-blast stoves.

- F. T. SISCO. "*Technical Analysis of Steel and Steel Works Material.*" 8vo, pp. 543. London, 1923: McGraw Hill Publishing Co., Ltd. (Price 25s.)

The object of the book is to show to the routine analyst, and to the many laboratory workers with little or no college training, the best-known methods for the analysis of special steels and steelworks material. Special emphasis is laid upon the need of speed in analytical control. It is not attempted to direct how a laboratory should be operated, but examples of steel laboratory work are presented, and different classes of work are cited, showing methods for the rapid and efficient handling of such work; in so doing the author has held to the colloquialisms of the works and laboratory without aiming too much at the use of highly scientific terminology. The book does not deal with the sampling and analysis of coal, coke, oil, water, and gas, on account of the desire to keep the size of the volume within a reasonable compass.

- F. TWYNAM. "*Wave-Length Tables for Spectrum Analysis.*" 8vo, pp. 106. London, 1923: Adam Hilger, Ltd.

This book contains a collection of tables useful for the purposes of spectrum analysis. Two kinds of tables are required for the purpose. The one should give, with an accuracy beyond question, the wave-lengths of radiations easily reproducible in the laboratory. The other should give the wave-lengths of distinctive lines of the elements. The tables of this latter kind selected for publication fall into three groups. First, tables of all the observed lines of each element grouped under the names of the elements. Secondly, spectrum lines of the elements arranged in order of the wave-lengths. Thirdly, lists of those lines of each element which are specially distinctive, as being those still showing when very little of the element is present. These, the most useful in modern spectrum analysis,

have not hitherto been collected in one volume. For these latter tables the results of Hartley, of Leonard and Pollok, and of A. de Gramont have alone been utilised, these being the authors who have given most attention to this problem.

The book is intended for use in the laboratory, and contains only matter essential for that purpose. It consists almost entirely of transcriptions, and a complete list of references is given at the end of the volume.

- W. TRINKS. "*Industrial Furnaces.*" 8vo, pp. 319. Vol. I. New York, 1923: John Wiley & Sons, Inc. London, 1923: Chapman & Hall, Ltd. (Price 22s. 6d.)

In 1919, 1920, and 1921 the author published in the *Blast-Furnace and Steel Plant* and in the *American Drop Forger* a series of thirty articles, and after very thorough revision and expansion these are now being issued as a complete work in two volumes, the first of which has just appeared, while the second is still in preparation. The first volume deals with the fundamental principles and facts which underlie all industrial heating operations and the science and art of furnace design. Rules are laid down for the determination of the size of a furnace to heat a certain amount of material in a given time to a given uniform temperature, and the heat losses from furnaces due to various causes and the quantity of fuel needed for heating unit weight of material in "in and out" furnaces worked under different conditions are investigated. The means employed to save heat and the heat consumption per unit of material are also exhaustively considered. A chapter is devoted to the question of the maintenance of furnaces, and the properties of materials which enter into their construction, and finally the arrangement and position of ports, flues, and stacks, their size and influence upon the circulation of the gases, are dealt with.

- F. B. HOWARD WHITE. "*Nickel: The Mining, Refining, and Applications of Nickel.*" Small 8vo, pp. 118. London, 1923: Sir Isaac Pitman & Sons, Ltd.

The book opens with an historical account of nickel followed by a description of its occurrences in nature, with a list of the nickel-bearing minerals. The processes of extraction of the metal from its ores and its refining are clearly set forth, with notes on the physical properties of nickel, and its mechanical and heat treatment. Some interesting notes on nickel coinage are presented, with tables showing the denominations of the coins and alloys used in coinage by the various nations of the world. A curious fact is that Great Britain and China are the only two large countries which have not yet adopted nickel coinage. The other well-known applications of nickel as an alloy metal are also dealt with.

- "*Research and Methods of Analysis of Iron and Steel at Armco.*" 8vo, pp. 220. Second edition. Middletown, Ohio, 1920: The American Rolling-Mill Company. (Price \$4.)

The book embodies the results of research work on the corrosion of iron and steel, with special reference to Armco ingot iron. The remaining chapters deal with magnetic testing of sheet steel for electrical purposes, the microscopical and physical testing by which the properties of metals are controlled, and methods for the analysis of iron and steel for the determination of aluminium, carbon, chromium, vanadium, copper, hydrogen, iron, manganese, molybdenum, nickel, nitrogen, oxygen, phosphorus, silicon, sulphur, and titanium, with notes on the determination of spelter coating on sheets and wire.

"*Tables Annuelles de Constantes et Données Numériques : Extraits du Volume IV.*" *Art de l'Ingénieur et Métallurgie.* 4to, pp. 1217-1379. *Données Numériques d'Électricité, Magnétisme et Electrochimie.* 4to, pp. 627-1016. Published under the patronage of the International Research Council and the International Union of Pure and Applied Chemistry, with the supervision of Mr. Charles Marie, General Secretary. Paris 1922 : Gauthier Villars et Cie.

Volume IV. of this publication, of which the present extracts form a part, is the first to be issued since 1913, and it contains such numerical data as have been collected since that date. The parts to which this notice relates give the latest information in accessible form concerning the constants of engineering materials, the properties of metals and alloys, magnetism, and electrochemistry. A study of the data will show that the research work relating to engineering, metallurgy, and electricity has progressed somewhat irregularly during the past few years. It is hoped that individuals engaged in research may be able to assist by releasing for publication numerical information now in their possession or carry out independent investigations to fill in important gaps.

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